VOLUME 106 PART A NUMBER 27 JUNE 1959

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

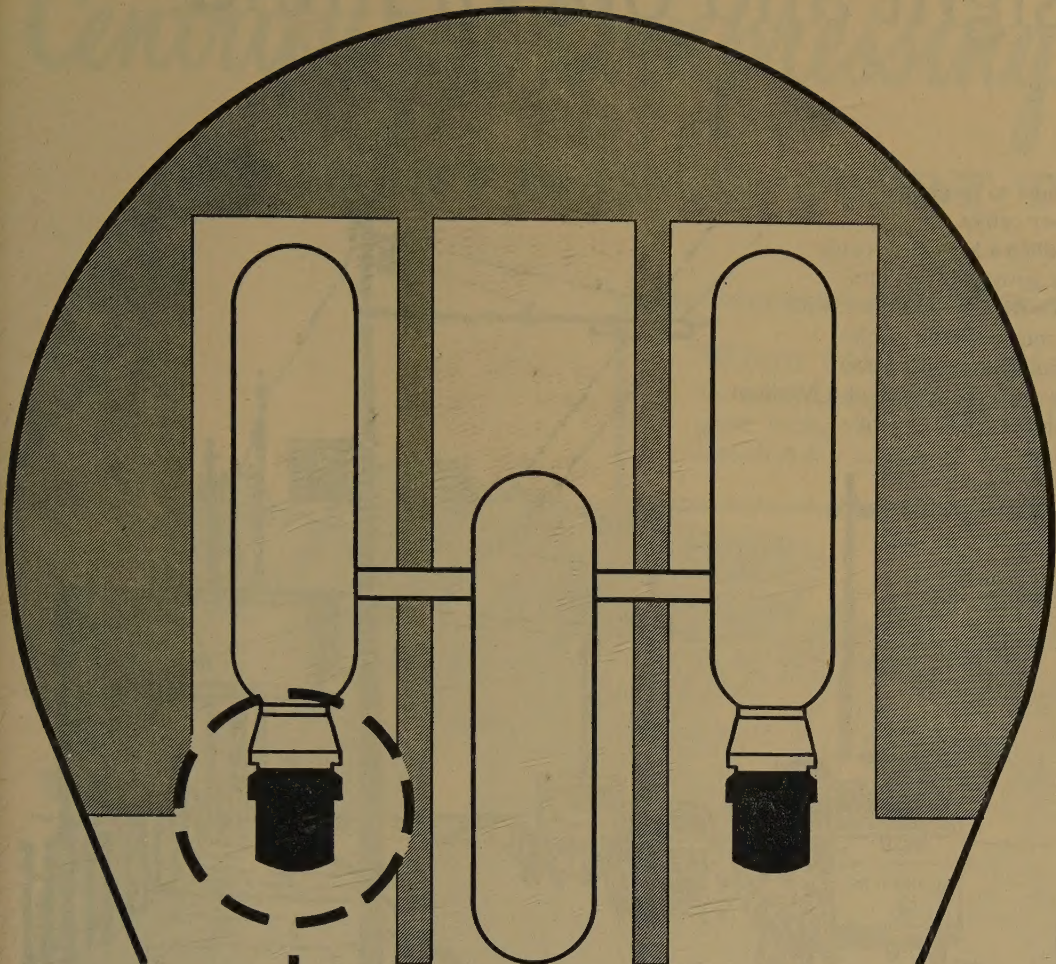
FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

SAVOY PLACE · LONDON W.C.2

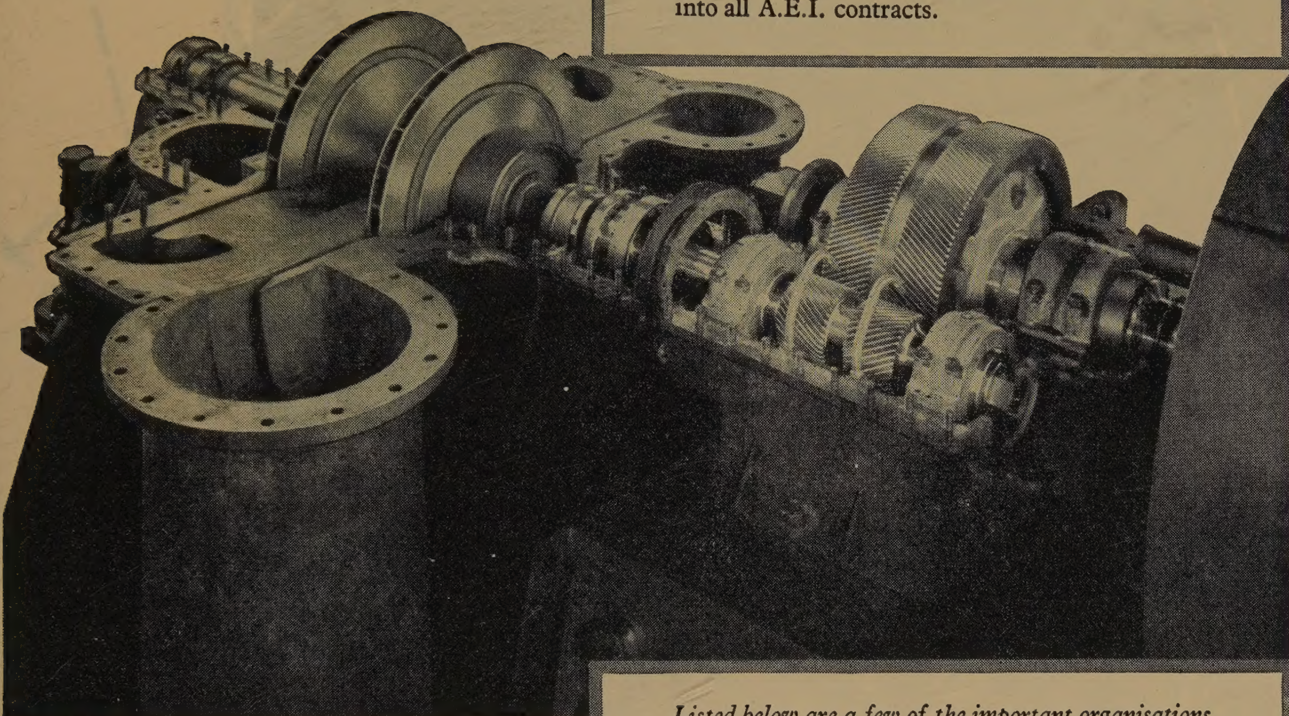
Price Ten Shillings and Sixpence



Centrifugal Compressing Plant

OF EVERY SIZE—OF EVERY TYPE

When calling for tenders...
for compressing plant of any type, consider the great background of experience which is built into all A.E.I. contracts.



Listed below are a few of the important organisations that have entrusted their compressing plant to the A.E.I. Group.

College of Aeronautics, Cranfield
Consett Iron Co. Ltd.
Gas Boards
J. & E. Hall Ltd.
Kodak Ltd.
National Coal Board
New Consolidated Gold Fields Ltd., S.A.
Richard Thomas & Baldwins Ltd.
Rolls-Royce Ltd.
Woodall Duckham Construction Co., Ltd.

AEI

COMPRESSORS, BLOWERS, BOOSTERS, EXHAUSTERS, SUPERCHARGERS

Publication G12131 will be sent on request.

For information on any compressing plant problem telephone **RUGBY 2121** Ext. 363

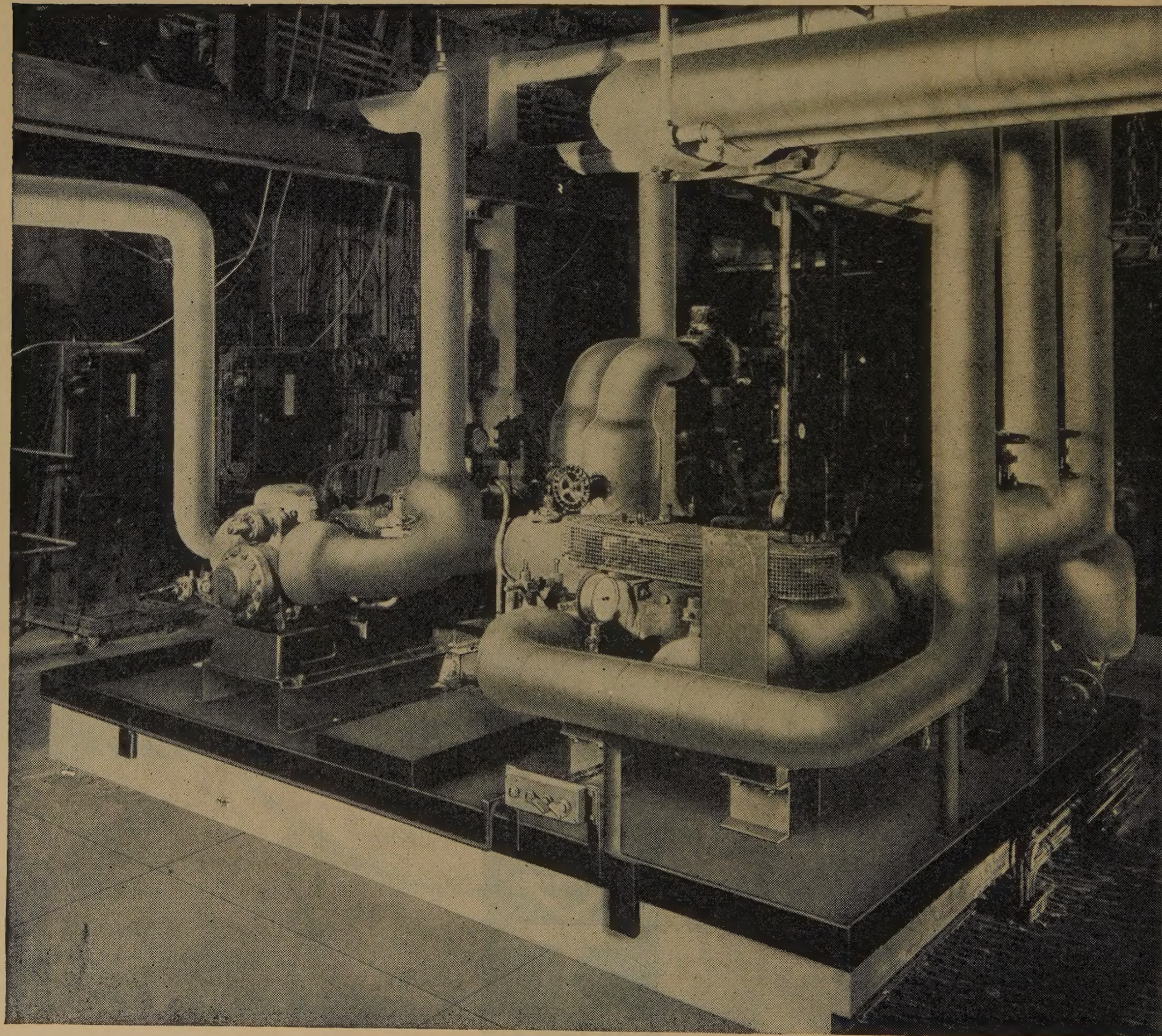
ASSOCIATED ELECTRICAL INDUSTRIES LIMITED

HEAVY PLANT DIVISION RUGBY AND MANCHESTER, ENGLAND

A5345

Oil

A section of the pumping and heating units at Littlebrook 'C' power station

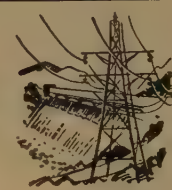


CONTROL

To some, control is a matter of manual dexterity, but to industry it is a highly complex affair. At S.T.C. an immense amount of research is done to solve the many complicated problems of remote, local and programmed control. This, plus the most modern production methods and many years' experience, are reasons why S.T.C. produces the world's finest, most efficient control equipment in the following fields:

CONTROL FOR POWER AND INDUSTRY

Constant supervision and fully safeguarded control at any distance and over a minimum number of signalling channels for gas, water, electrical and industrial installations.

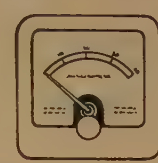


CONTROL FOR RAILWAYS

Describing equipment to indicate the position, class, destination, speed and order of trains, and automatically direct their movements.

TELEMETERING

Centralised local and remote readings of individual loads, total load and feeder flow for all electricity undertakings.

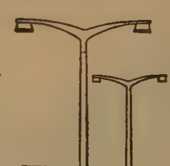


PROCESS CONTROL

Monitoring diagrams of various types to display the condition and direct the activities of industrial processing systems.

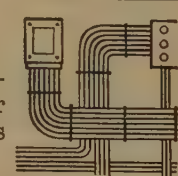
STREET LIGHTING CONTROL

For centralised control of all types of street lighting systems, shop window lighting, space heating of buildings etc.



CONTROL CABLES

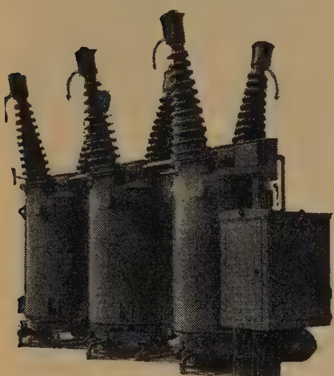
Cables suitable for all forms of remote control of power switching. For particular applications, cables with special properties are available.

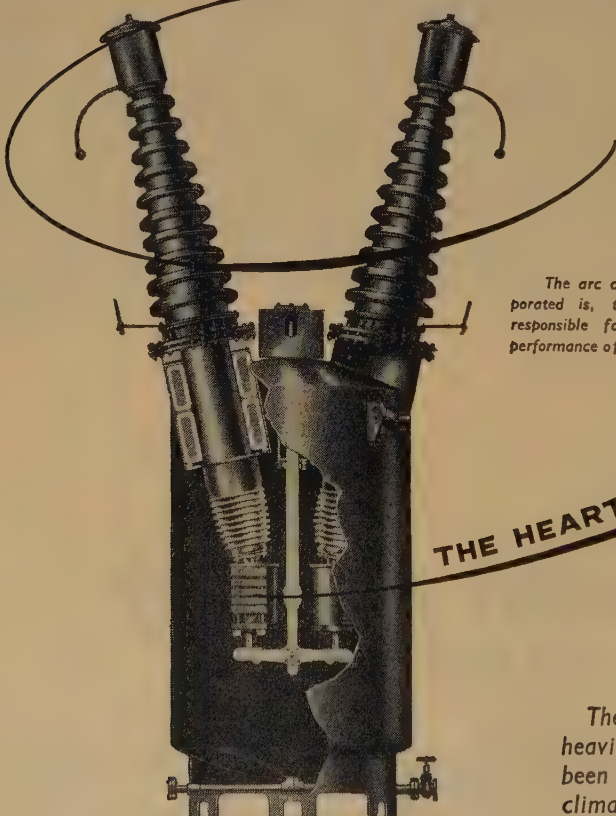


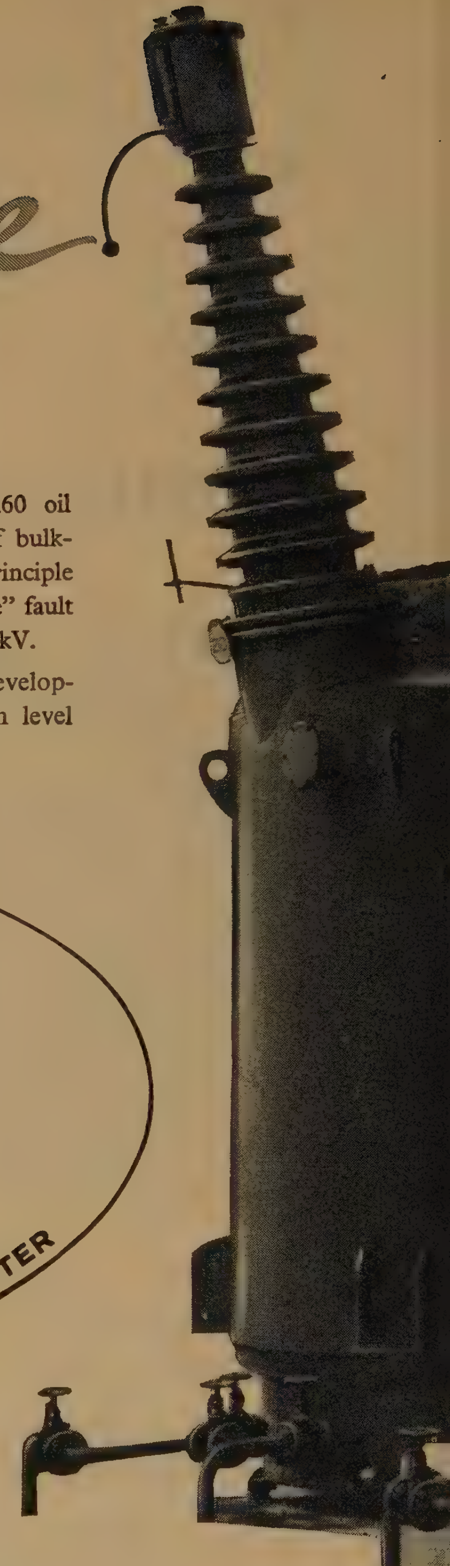
Standard Telephones and Cables Limited

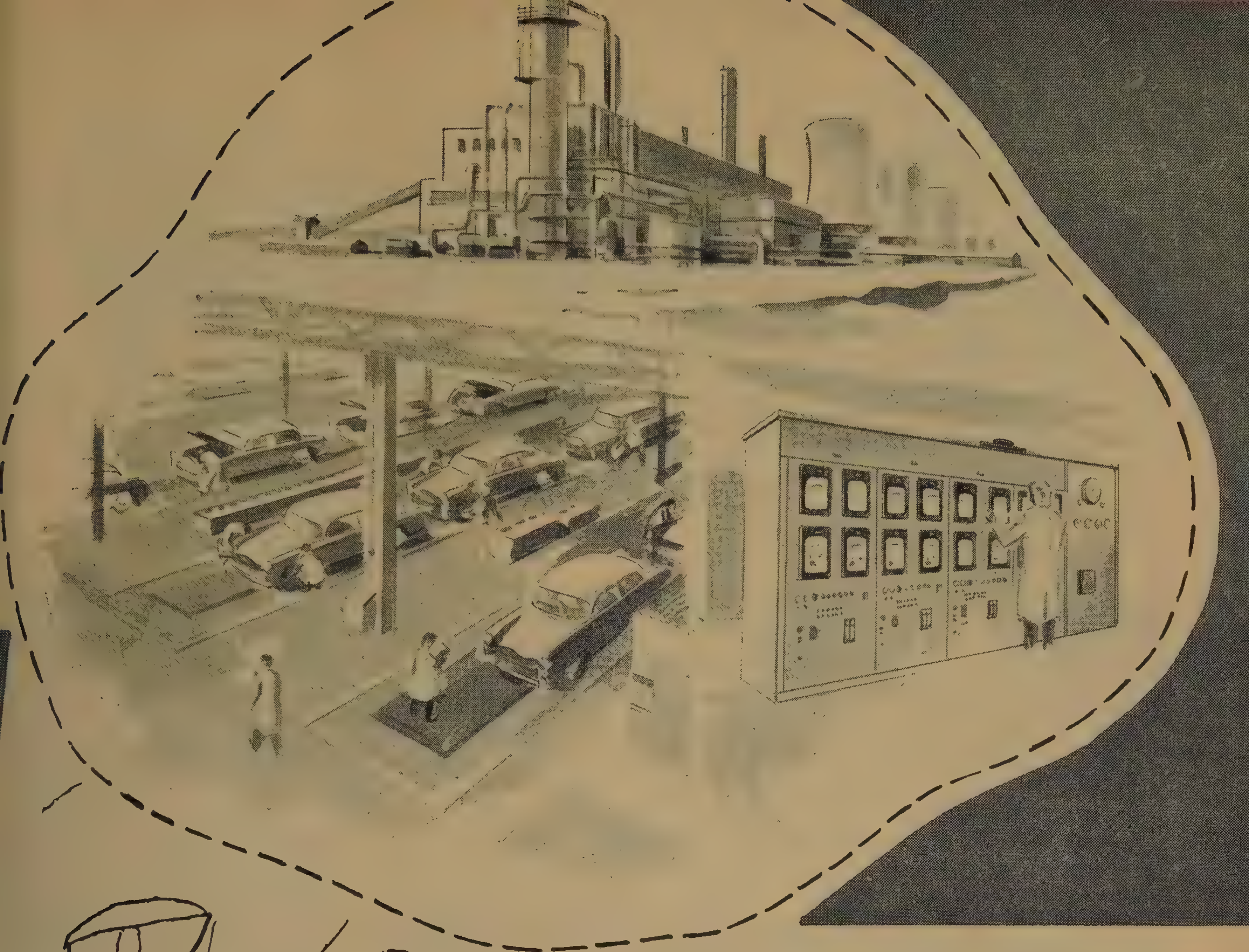
TELECOMMUNICATION ENGINEERS

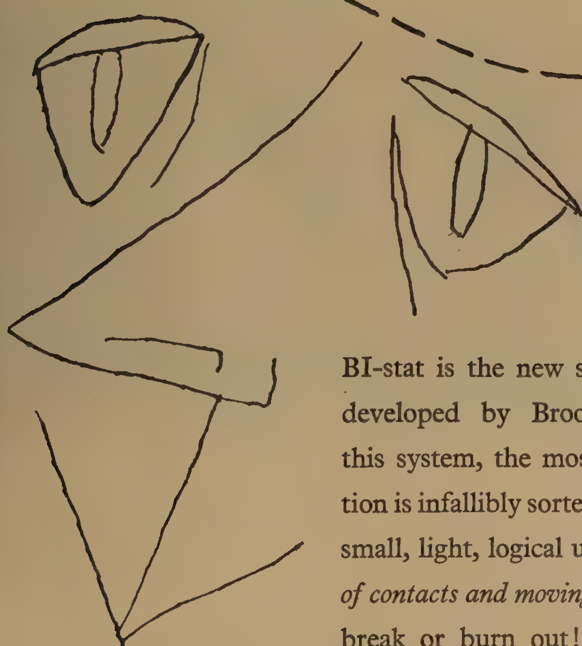
CONNAUGHT HOUSE · 63 ALDWYCH · LONDON W.C.2











WHAT is BI-stat CONTROL?

BI-stat is the new static control system developed by Brookhirst Igranic. In this system, the most complex information is infallibly sorted and transmitted by small, light, logical units—*entirely devoid of contacts and moving parts*. Nothing to break or burn out! And encapsulated housings ensure complete protection from dirt, moisture or fumes. BI-stat equipment introduces new conceptions of efficiency, reliability and long life. It can be used to great advantage in motor control schemes, replacing conventional relays and other auxiliary switching devices, particularly for installations where processes are complicated, stoppage costly or maintenance difficult. Find out how BI-stat may help you to solve tomorrow's control problems today. Write for leaflet 1809 giving full details.

BROOKHIRST IGRANIC LIMITED

Sales Headquarters: IGRANIC WORKS BEDFORD

HEAD OFFICE & EXPORT SALES DIVISION : BROOK HOUSE PARK LANE LONDON W1

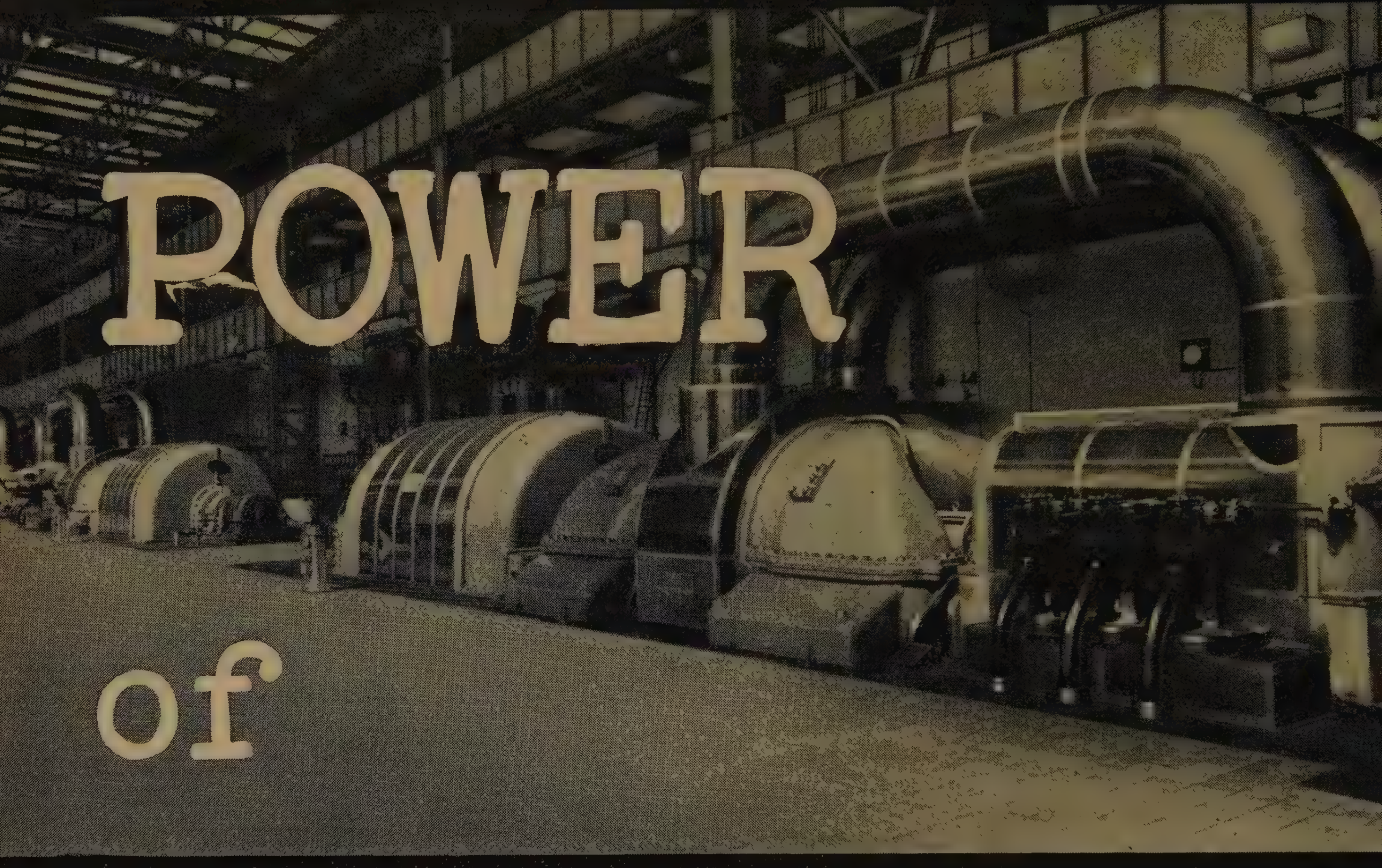
AREA OFFICES: BIRMINGHAM · BRISTOL · CARDIFF · EAST ANGLIA · GLASGOW · LEEDS · LONDON · MANCHESTER MID. SOUTH · NEWCASTLE · NOTTINGHAM · SHEFFIELD

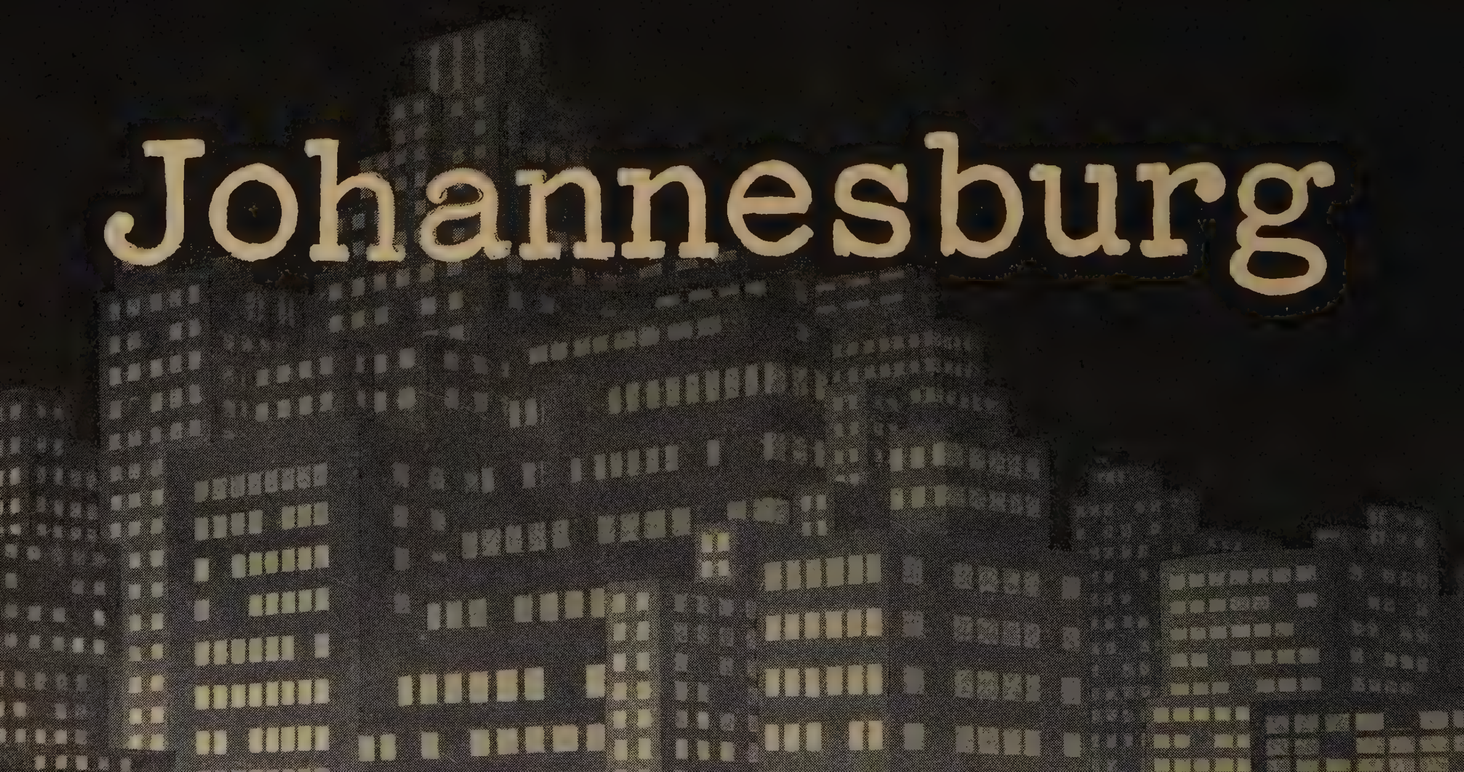
WORKS AT BEDFORD & CHESTER

A Metal Industries Group Company

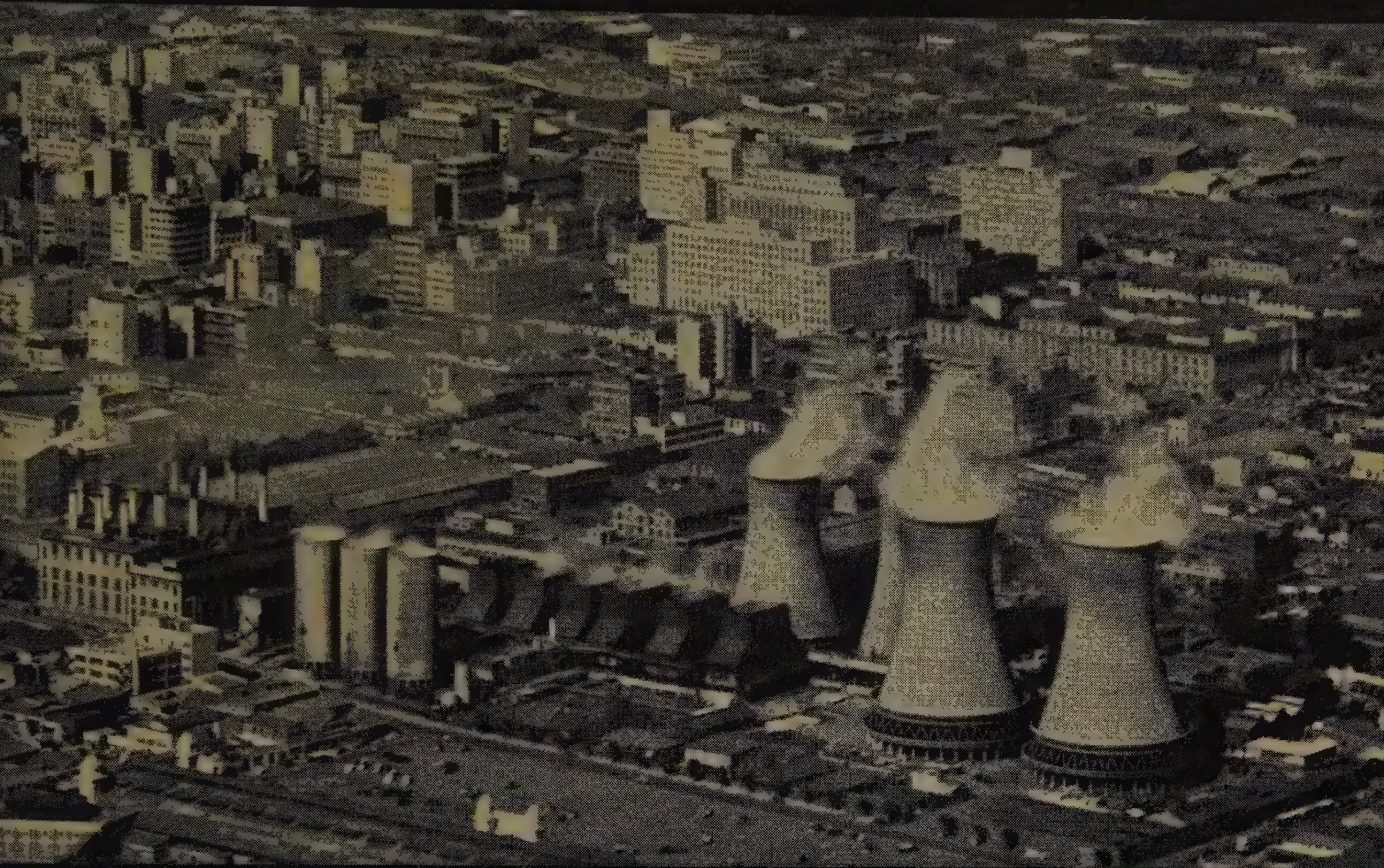
CVS 74A

The POWER of Johannesburg





Johannesburg, Transvaal! At night a fairyland of light, by day a bustling centre of commerce. A busy city, a modern city, a city powered by the G.E.C.



With the latest contract for two 60 MW turbo-generators, the number of G.E.C. sets in Johannesburg's four power stations will total twenty five and will provide three quarters of a million kilowatts. And so the G.E.C. serves Johannesburg with the power to keep a great city alive. A big job indeed—and just the job for the G.E.C. with its vast experience of electrical generation, distribution and control.

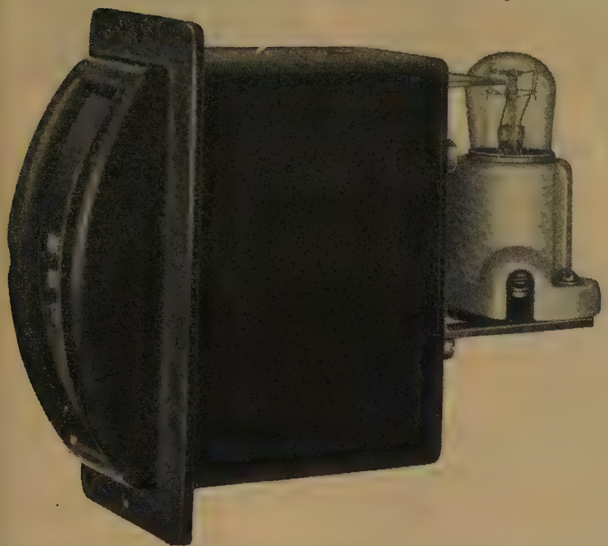
G.E.C. power generation

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND.
HEAD OFFICE: MAGNET HOUSE KINGSWAY LONDON WC2

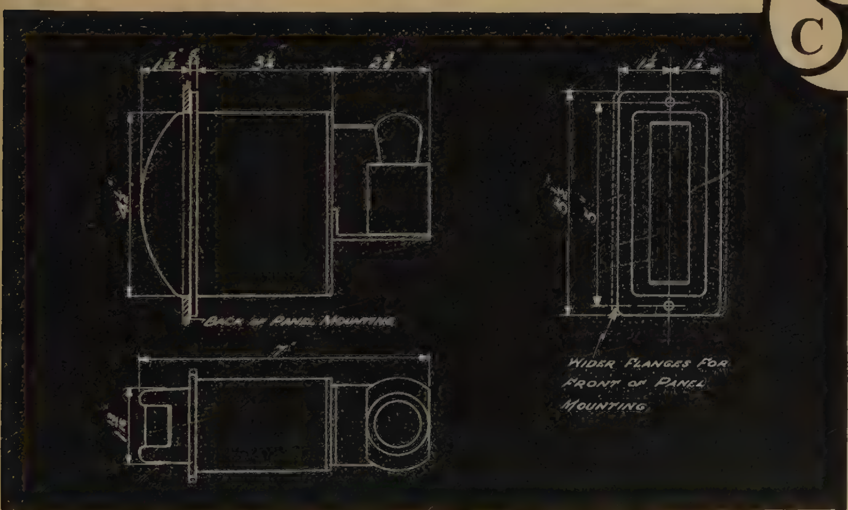
NALDERS INSTRUMENTS

SMALL ILLUMINATED EDGEWISE

SCALE ILLUMINATED by Total Internal Reflection in a Perspex scale-plate, from an External electric lamp



3½" SINGLE ELEMENT-VERTICAL PATTERN



AS SUPPLIED (IN QUANTITY) TO THE BRITISH TRANSPORT COMMISSION FOR THE NEW HIGH VOLTAGE RAILWAY ELECTRIFICATION SCHEME

ADVANTAGES

1. **SMALL SIZE**—little panel space
2. **EFFICIENT & UNIFORM** illumination
3. **DUSTPROOF**—no light-holes in the case
4. **EXTERNAL LAMP**—easily replaceable

Available as a SINGLE or DOUBLE element Moving Coil or Moving Iron Instrument. VERTICAL or HORIZONTAL Pattern.

Further details about these instruments will gladly be sent on request.

Please quote IE6E

NALDERS PRODUCTS INCLUDE:

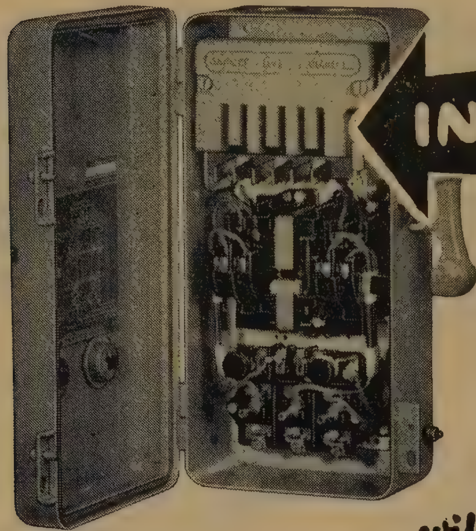
VOLTMETERS VECTORMETERS POWER FACTOR METERS
AMMETERS SYNCHROSCOPES and PROTECTIVE RELAYS
WATTMETERS FREQUENCY METERS 'BIJOU' CIRCUIT BREAKERS

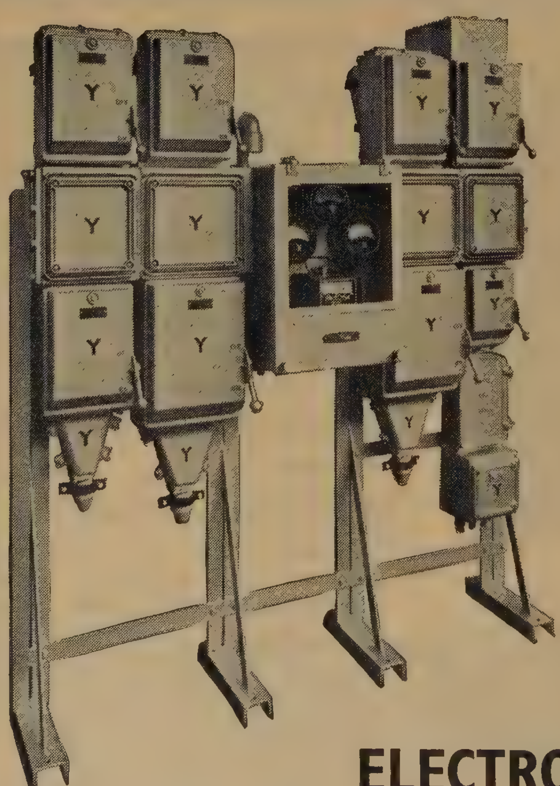
NALDERS MAKE EVERY TYPE OF MEASURING AND GRAPHIC RECORDING ELECTRICAL INSTRUMENTS

They all fully comply with the current BRITISH STANDARD 89

NALDER BROS. & THOMSON LTD., Dalston Lane Works, London E.8. Tel: CLIssold 2365 (4 lines) Grams: Occlude Hack London

BMJ





THE INSTITUTION OF ELECTRICAL ENGINEERS

presents

THE INQUIRING MIND

a film outlining the opportunities for a career in the field of electrical engineering

Producer: Oswald Skilbeck *Director: Seafield Head*

Commentator: Edward Chapman

Copies of the film may be obtained on loan by schools and other organisations for showing to audiences of boys and girls or others interested in a professional career in electrical engineering. The film is available in either 35mm or 16mm sound, and the running time is 30 min.

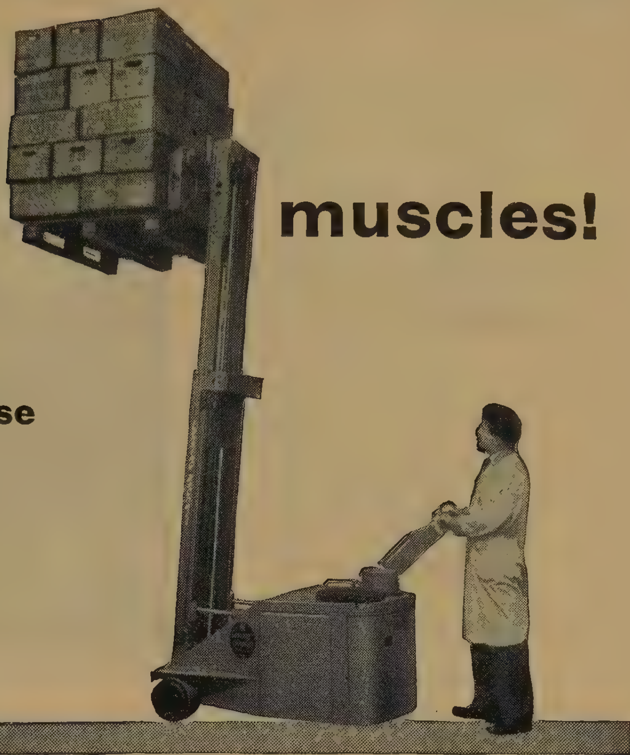
Application should be made to

THE SECRETARY

THE INSTITUTION OF ELECTRICAL ENGINEERS

SAVOY PLACE, LONDON, W.C.2

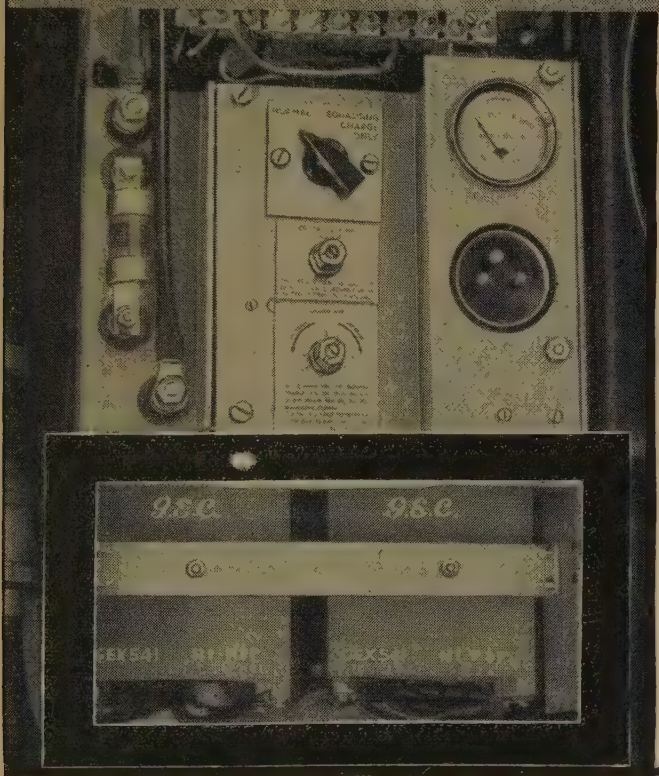
Strength without muscles!



**for their latest Fork-lift Truck
Lansing Bagnall chose**

G.E.C.

GERMANIUM RECTIFIERS



for compactness
Small size is very important in this application. The new GEX 541 rectifier stack gives maximum rectified power per unit volume.

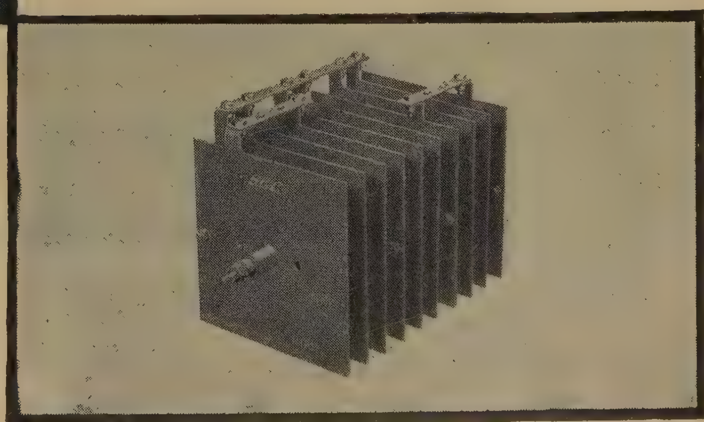
for lightness
Germanium Rectifiers are the lightest type of rectifier available for most applications. The GEX 541 weighs only 10% of the equivalent conventional rectifier.

for efficiency
Like all germanium rectifiers in the G.E.C. range, the GEX 541 offers low forward resistance and corresponding increases in efficiency and regulation.

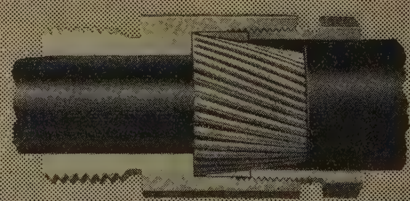
THE BASIC GEX 541 is a germanium junction diode. Single units are available for such applications as DC blocking and gating. Complete rectifier stacks can be supplied, finned or unfinned, for the price of the constituent diodes only, suitable for currents up to 160 amps. or D.C. output voltage of up to 900 volts.

**For Data Sheets
and further information
please write to the
Semiconductor Division**

G.E.C. Semiconductor Division
School St., Hazel Grove, Stockport, Cheshire
Telephone: Stepping Hill 3811
or for London Area ring Temple Bar 8000, Ext. 10



INDEX OF ADVERTISERS



THE PROCEEDINGS OF
THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 106. PART A. NO. 27. JUNE 1959

621.315.616

The Institution of Electrical Engineers
Paper No. 2814 M
Dec. 1958
©

SILICONE ELECTRICAL INSULATION

By J. H. DAVIS, Associate Member.

(*The paper was first received* 2*nd May, and in revised form* 10*th November*, 1958. *It was published in December*, 1958, *and was read before a joint meeting of the* MEASUREMENT AND CONTROL *and* UTILIZATION SECTIONS 6*th January*, 1959.)

SUMMARY

Silicone fluids, compounds, rubbers and resins are described in terms of their chemical structure and physical properties, alone or in combination with inorganic insulating materials.

There follows a brief review of thermal endurance evaluation and the position of silicone insulation in British and other Standards. Applications are then discussed, with reference to conductors, cables, rotating machines, transformers and other electrical apparatus. Economic aspects are considered, and it is shown that, though silicones are more expensive than organic materials used for lower temperature insulation, frequently there are compensating improvements in performance, reliability or installation cost.

The paper also notes desirable improvements in properties and processing requirements. It is considered that cost will probably restrict the use of silicone insulation at lower temperatures, but that the trend towards replacement of Class B insulation with silicones will continue. Novel and economical manufacturing techniques with silicone rubbers may offer particular advantages.

(1) INTRODUCTION

Organo-silicon chemistry was founded in the nineteenth century work of Berzelius, Ebelman, Crafts and others,[1] leading to the extensive work of Kipping at Nottingham University from 1896 until after 1930.[2] The description 'silicone' is now applied to polymers containing siloxane, i.e. Si—O units with organic groups attached by carbon-to-silicon bonds. Chemically, they are best described as organo-polysiloxanes, and their commercial development began with research in the United States, initiated in 1932, to find more heat-stable electrical insulating resins with which to coat the newly-developed fabric, glass cloth. The first silicone of importance was an ignition sealing-compound for aircraft engines, introduced in 1942. From 1943 onwards commercial production increased rapidly in the United States and a series of resins and fluids were produced in 1943, to be followed by the first appearance of a silicone rubber in 1944.

In a paper[3] read before a joint meeting of The Institution of Electrical Engineers and the Plastics Group of the Society of Chemical Industry in 1945, Dr. S. L. Bass described the properties of these new chemical products. They were imported from the United States until production began here in 1952 and soon covered the whole range of commercially used fluids, compounds, rubbers and resins. Their industrial uses have grown rapidly.

Electrical applications nearly all rely on their thermal endurance combined with good dielectric properties and moisture resistance. Thermal endurance is given by the Si—O bond, with a strength of 89·3 kcal/mole, compared with 58·6 kcal/mole for the C—C bond in typical organic materials. The proximity of the strongly ionic Si—O bond also appears to reduce the activity of the organic side-groups.[4]

Various silicones have also proved useful as release agents, water-repellent treatments for textiles and masonry, anti-foaming agents, polish additives, constituents of heat-resistant paints and for other applications.

(2) SILICONE FLUIDS AND COMPOUNDS

(2.1) Silicone Fluids

Dimethyl silicone fluids are manufactured in viscosities ranging from below one centistokes to several million centistokes, measured at 25° C.

Their basic structure is given by the formula

$$\begin{array}{c} CH_3 \\ | \\ H_3C\text{—}Si\text{—} \\ | \\ CH_3 \end{array} \left[\begin{array}{c} CH_3 \\ | \\ O\text{—}Si\text{—} \\ | \\ CH_3 \end{array} \right]_n \begin{array}{c} CH_3 \\ | \\ \text{—}O\text{—}Si\text{—}CH_3 \\ | \\ CH_3 \end{array} \quad . \quad . \quad . \quad (1)$$

which may be compared with that of the straight-chain paraffin hydrocarbons:

$$\begin{array}{c} H \\ | \\ H\text{—}C\text{—} \\ | \\ H \end{array} \left[\begin{array}{c} H \\ | \\ C\text{—} \\ | \\ H\text{—} \end{array} \right]_n \begin{array}{c} H \\ | \\ \text{—}C\text{—}H \\ | \\ H \end{array} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Only small changes in electrical properties occur over a wide temperature and frequency range[5] (Fig. 1), a feature which is

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.
Mr. Davis is with Midland Silicones, Ltd.

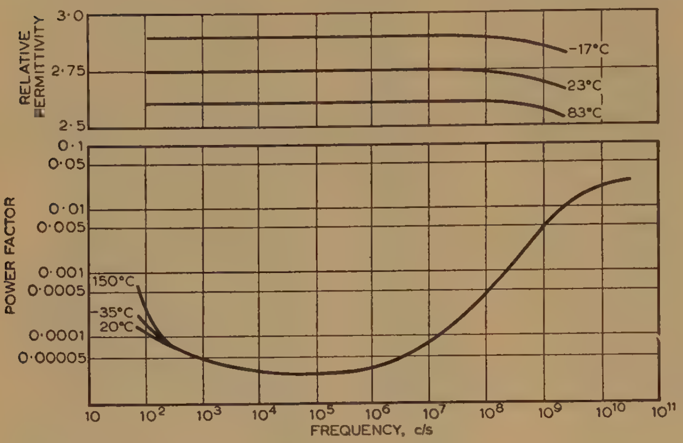


Fig. 1.—Dimethyl silicone fluid of 1000 cS viscosity.
Effect of frequency and temperature on power factor and permittivity.

characteristic of silicones in general. The dimethyl fluids have lower thermal endurance than silicone rubbers or resins, but for most applications those with a viscosity above 100 cS may be used continuously at 200° C in the absence of oxygen, or at 150° C in its presence.

Fluids in which some of the methyl groups in formula (1) are replaced by phenyl groups have a wider working-temperature range but slightly higher values of power factor.

Because of their small change in viscosity with varying temperature, silicone fluids are used as dashpot fluids for switchgear-delay mechanisms and similar applications.

(2.2) Silicone Compounds

These are made from silicone fluids by incorporating inert fillers, and resemble clear organic grease, but will withstand temperatures from below −50° C to above 200° C without appreciable change in consistency. Typical properties are shown in Table 1.

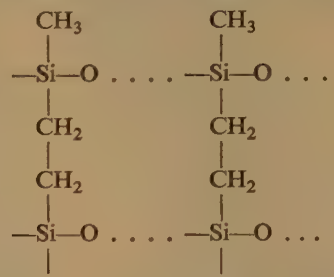
They are applied to components by spreading or by grease gun to form a water-repellent, anti-tracking coat or filling. Alternatively, they can be dispersed in aromatic or chlorinated hydrocarbon solvents and applied by brushing or spraying.

(3) SILICONE RUBBERS

(3.1) Chemical Structure[6–9]

If in formula (1) *n* has a value of several thousands, highly viscous fluids of gum-like viscosity are obtained. Silicone rubbers are manufactured by compounding these with inorganic reinforcing fillers such as silica, titanium dioxide and zirconium silicate, which largely determine the properties of the stock. Additives, e.g. ferric oxide, are sometimes included in small quantities to improve specific properties.

Strong oxidizing agents such as benzoyl peroxide and 2 : 4 dichloro-benzoyl peroxide are incorporated. When heated, e.g. to 125° C for benzoyl peroxide, cross-linking occurs between polymer chains, mainly by the formation of ethylene bridges.



. . . . (3)

Recently-developed stocks contain gums with some vinyl side groups which enable less reactive curing agents, like ditertiary butyl peroxide, to be used. Among other advantages, this permits better curing of thick sections and gives lower compression set. Carbon blacks are compatible with this type of curing system, and may be added to form conducting rubbers.

Curing by irradiation is an alternative to chemical methods.[7, 10] High-energy electrons are particularly suitable; in about one minute, the application of 20 megarads can provide a cure equivalent to a 24-hour bake at 250° C. This treatment can be given by particle accelerators and may prove economical in the future for continuously extruded cable, sleeving and tapes.

Certain stocks may be cured without heating by the addition of an organo-metallic catalyst, which initiates a condensation reaction.[7] Carbon blacks are compatible with this curing system also.

(3.2) Physical Characteristics

Despite great improvements since their introduction, silicone rubbers still have lower tensile and tear strengths than organic rubbers (Tables 2 and 3).

Table 1

PROPERTIES OF TYPICAL SILICONE COMPOUND

Physical properties		Electrical properties	
Penetration,* unworked	190 to 230	Volume resistivity, up to 200° C, ohm-cm	10^{12}
Penetration,* worked	300 max.	Relative permittivity between 100 c/s and 10 Mc/s	2·8
Bleed,† 24 h at 200° C	10 max.	Power factor between 100 c/s and 10 Mc/s	0·001
Volatility,† 24 h at 200° C	2 max.	Electric strength§ at 10 mils, volts/mil	500 min
Specific gravity at 25° C	0·98–1·03		
Coefficient of expansion (25° C to 200° C) per deg C	7×10^{-4}		

* A.S.T.M. D.217—48 or I.P. 50/48. † M.O.S. Aircraft Material Specification D.T.D. 825. § M.O.S. D.T.D. 900/4298.

Table 2

IMPROVEMENTS IN PHYSICAL CHARACTERISTICS OF SILICONE RUBBER

Grade of silicone rubber	Year of introduction	Tensile strength (B.S. 903)	Elongation at break (B.S. 903)
		lb/in²	%
A	1944	450	80
B	1947	750	70
C	1949	700	280
D	1953	900	280
E	1957	1 500	550
Typical natural rubber		3 500	700

Table 3

COMPARATIVE HEAT-AGEING CHARACTERISTICS OF NATURAL, HYPALON AND SILICONE RUBBERS

Time to reduce Elongation at Break (BS. 903) to 100%

Heat-ageing temperature	Neoprene or typical natural rubber	Hypalon*	Typical silicone rubber†
deg. C			
125	< 7 days	—	—
150	< 1 day	5 days	—
200	<15 min	30 min	3 months
250	—	—	1 month
300	—	—	2 days

* One of the most heat-resistant synthetic rubbers.
† As used for extruded cables and sleeving; grade D in Table 2.

Many stocks of widely varying characteristics are available. Electrical manufacturers often buy these from the rubber processor as fabricated components, or may use them directly as paste stocks for bonding, void filling and encapsulation.

Good resistance is shown to chlorinated diphenyl dielectric fluids, but some commonly used liquids, including paraffin oils, cause swelling. Fluorinated and nitrile silicone rubbers with greatly improved solvent resistance have been developed for special applications, mainly in aircraft, and further developments are likely.

Silicone-rubber insulation is more water resistant than resinous materials, because of its greater flexibility and resistance to cracking.

(3.3) Sleeving and Tapes[11]

These are available with or without glass-fibre reinforcement, and are used widely at temperatures above 100° C. The tapes can be bonded with a solventless silicone-rubber adhesive, applied during taping, or the glass-reinforced tapes may carry a layer of pressure-sensitive or hot-setting adhesive.

Tapes are now available which will bond together without heat or pressure, and should prove attractive for many purposes because of their easy application.

(3.4) Void Filling and Encapsulation

Earlier paste stocks which were used for void filling bubbled during cure, but those recently developed do not have this disadvantage.

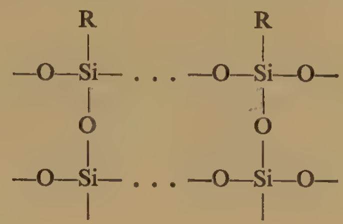
The cold-curing silicone rubbers are an important example. Available in consistencies ranging from a heavy fluid (about 7 000–11 000 cS) to a heavy paste, their setting time may last from a few minutes to several hours, depending on the quantity of catalyst added. Heating accelerates the cure, while refrigeration or solvent dispersion prolongs the pot life of the catalysed stock.

Environmental protection over a wide temperature range can be provided for components, and good penetration is obtained in coils of fairly open section by vacuum impregnation with the more fluid type of stock. To obtain better flow or thin builds, a dispersion in white spirit, xylene or other solvents can be used. Air-drying inorganic or silicone-resin primers are often used to improve adhesion to components.

(4) SILICONE RESINS

(4.1) Chemical Structure

These are usually supplied as solutions in xylene, toluene or other aromatic solvents, or in acetone. They are cured by heating, which first removes the solvent and then causes several reactions, including condensation of hydroxyl groups and oxidation of organic side groups. Strongly cross-linked structures are formed:



. . . . (4)

The organic groups R are usually methyl or phenyl.

Resins with a high proportion of phenyl groups may have lower physical strength, particularly at elevated temperatures. However, their electrical characteristics are generally better than those of resins with low or zero phenyl content, mainly because of their high degree of flexibility and resistance to crazing during curing and heat ageing.

Silicone resins are used with mica and inorganic fabrics, somewhat similarly to organic resins in Class B insulation.

(4.2) Bonding and Laminating Resins[12, 18]

These are used for bonding glass cloth, asbestos paper or mica. For different resins the necessary laminating pressures may vary from about 10 to 1 000 lb/in².

Glass-cloth laminates made from the low-pressure type retain good physical properties after heat ageing, but have rather low electric strength. Some high-pressure laminating resins give similar results, while others with a greater phenyl content are used to make laminates of higher electric strength but slightly poorer physical properties. Their characteristics are compared in Fig. 2.

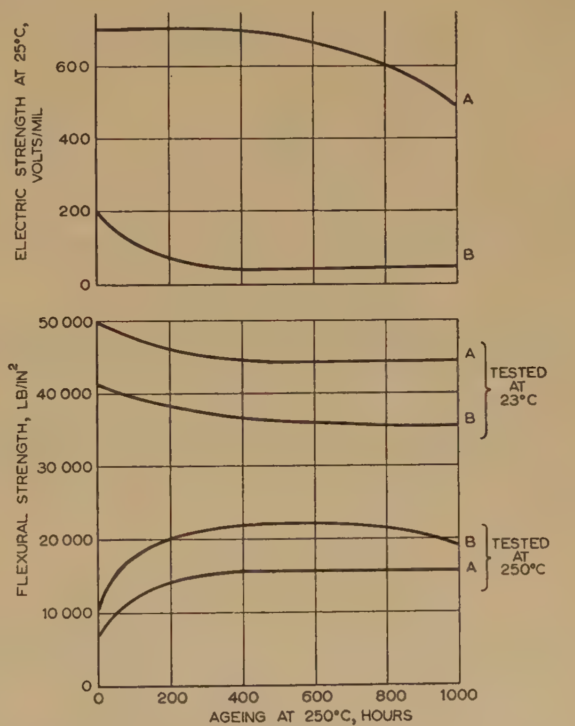


Fig. 2.—Heat-ageing characteristics of silicone-resin-bonded glass-cloth laminates.

A. High-pressure laminating resin with high phenyl content.
B. Low-pressure laminating resin with low phenyl content.
Laminates were $\frac{1}{16}$ in thick. Electrical breakdown values measured at 50 c/s using $1\frac{1}{2}$ in and 3 in diameter electrodes.

(4.3) Conductor and Cloth-Coating Resins

These are more flexible than the laminating resins, and are applied to glass-cloth and asbestos or glass-covered conductors. The most flexible and heat-resistant type of resin requires curing temperatures of 250° C or above, though this may be reduced to about 200° C by catalysis. This temperature is outside the range of many commercial cloth-coating towers, for which resins have been developed which become tack-free after a short time at 150° C. The comparative heat-ageing characteristics of silicone and high-temperature organic resins are illustrated in Fig. 3.

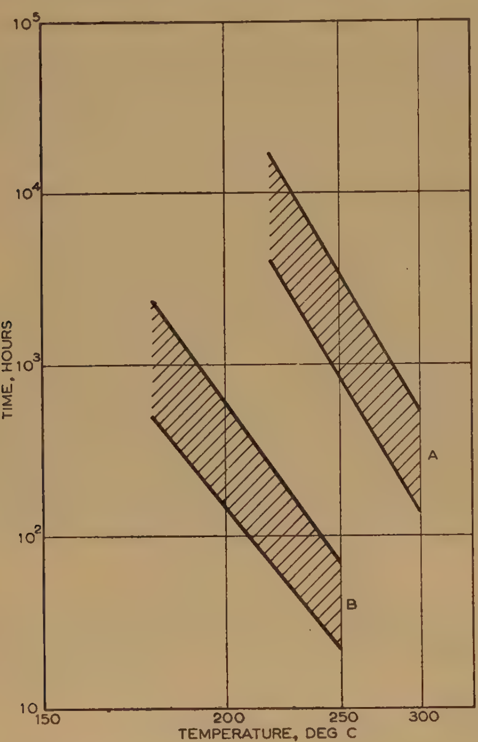


Fig. 3.—Comparative heat-ageing characteristics of organic and silicone resins.

Time to reduce electrical strength of varnished glass cloth by 50%.

A. Silicone varnishes.
B. High-temperature organic varnishes.

Electrical breakdown tests on varnished glass cloth may give variable results depending on the mechanical stresses applied to the resin film. The above results were obtained without measured flexing of the test samples, but show good agreement with life test results on actual equipment, as described in references 13, 29, 32 and elsewhere.

The equipment for curing varnished glass-covered conductors is generally capable of temperatures near or above 400° C, which enables good rates of production to be achieved with even the high-temperature curing resins.

(4.4) Impregnating Varnishes

Motors impregnated with the early silicone impregnating-varnishes proved their excellent thermal endurance in accelerated life tests.[13, 14] However, curing was a lengthy process, beginning with solvent removal at 90° C and proceeding by intermediate stages to a final bake at 250° C.

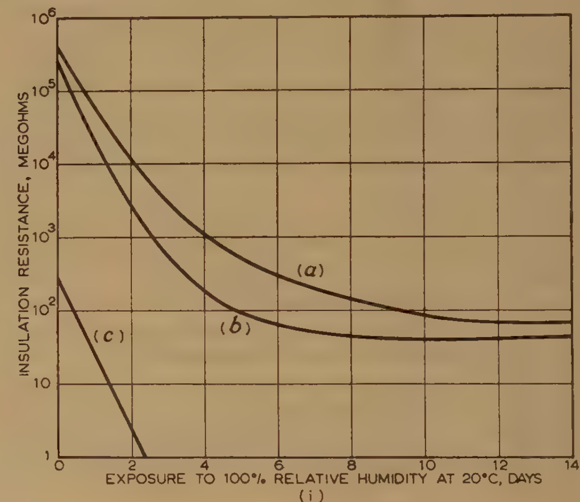
Subsequent improvements enabled most apparatus to be cured directly at 200° C. A final bake at higher temperature is still given if maximum bond strength is required, while a solvent-removal stage at 90° C is desirable to prevent bubbling in coils of deep section. Prior to impregnation, silicone-insulated apparatus is usually baked for several hours at 200° C to improve the solvent resistance of insulation components.

Even after prolonged curing, silicone impregnating resins are rather thermoplastic at high temperatures.[15] This is sometimes disadvantageous, but helps to avoid crazing during temperature cycling and heat ageing. Typical oil-modified phenolic and alkyd impregnating varnishes are less thermoplastic, but also have poor values of bond strength when hot, while unmodified phenolic and epoxy resins show much better retention of bond strength at elevated temperatures, but are more brittle.

(4.4.1) Impregnated Asbestos.

Asbestos millboard components may be impregnated in silicone resins, preferably of 60% or more solids content and low viscosity, e.g. 20 cS. This gives good resin penetration and absorption, which is essential to ensure reasonable electrical properties when wet.

A useful and more economical insulation board, with the characteristics shown in Figs. 4(i) and 4(ii), is obtained by com-



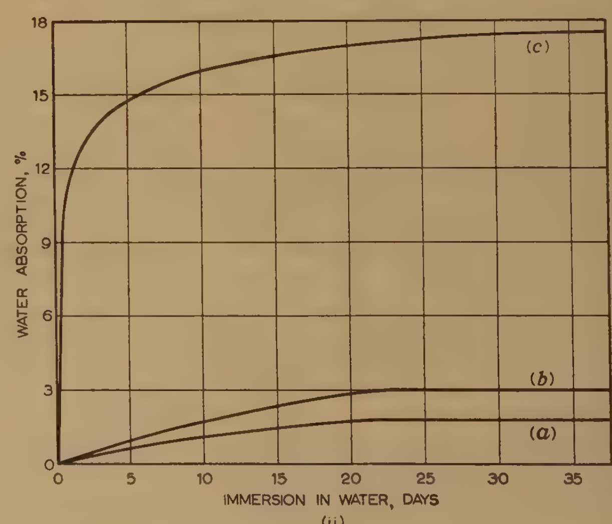


Fig. 4.—Characteristics of cement-asbestos board impregnated with silicone resin.

(i) Effect on insulation resistance.
(ii) Effect on water absorption.

(a) Phenolic paper laminate B.S. 1137, Type 1.
(b) Silicone-resin-impregnated cement-asbestos board.
(c) Untreated cement-asbestos board.

pletely impregnating cement-asbestos board (B.S. 737) in resins of this type. A maximum resin content of about 11% by weight is obtained in the treated board, compared with 50% or more for asbestos millboard.

Materials of this type are best restricted to low-frequency applications at low or medium voltage. A particularly useful feature of the impregnated cement-asbestos board is its high arc resistance in comparison with organic treatments.

(4.5) Organic-Modified Silicone Resins

Improved physical properties can be obtained by modifying suitable silicone-resin intermediates with additional organic groups, but there is some reduction in thermal endurance. Alkyd-modified silicone resins are used for coating glass-covered conductors, and as wire enamels[16] and impregnating varnishes.

An alkyd-modified silicone impregnating varnish has proved popular for traction and aircraft motors, because of its good thermal endurance and resistance to kerosene, oils and ester-based lubricants.

(4.6) Effects of Nuclear Radiation

Unlike silicone rubbers, the resins cannot be cured by practicable doses of irradiation. Silicone-resin-based insulation shows excellent resistance to degradation during long-term exposure to radioactivity, with no marked deterioration from doses up to 1 000 megarads at room temperature. As with other materials, radiation resistance is reduced at high temperatures.

(5) EVALUATION OF THERMAL ENDURANCE

Soon after the first silicone resins were produced, extensive accelerated life tests on silicone-insulated motors were initiated in the United States. By 1947 the results justified the proposal of 180° C as a suitable 'hottest-spot' temperature for Class H, the name given to this new insulation class. It was defined in American I.E.E. Standard No. 1,[19] as follows:

> Class H insulation consists of (1) mica, asbestos, fiberglass and similar inorganic materials in built-up form with binding substances composed of silicone compounds, or materials with equivalent properties; (2) silicone compounds in rubbery or resinous forms, or materials with equivalent properties. A minute proportion of Class A materials may be used only where essential for structural purposes during manufacture.

This followed the earlier classification in British, American and other Standards of materials as Class O, A, B and C, depending on their chemical composition, based mainly on the 1935 edition of Publication No. 34 of the International Electrotechnical Commission.

The proposal of 180° C as the Class H 'hot-spot' temperature was based on extrapolation of accelerated life-test results at higher temperatures, with due experimental allowances, but subsequent experience has shown this temperature to be conservative for a combination of mica, glass cloth and other inorganic insulation in combination with the most heat-resistant silicone resins. For such materials, a useful life of many years at temperatures of 200–220° C has been confirmed; for example, one of the early test motors has now been operating for over thirteen years at 240° C.

Class H was incorporated in the draft International Electrotechnical Commission document prepared at Philadelphia in 1954 together with the other new classes E (120° C) and F (155° C). The superior thermal endurance of polytetrafluorethylene and some silicone-resin based insulation, just described, is recognized by their inclusion in a subsidiary clause of Class C with a note of their limited performance above 225° C.

B.S. 2757: 1956, 'Classification of Insulating Materials for Electrical Machinery and Apparatus', is virtually identical with the 1954 I.E.C. document, and classifies working-temperature limits for insulation referred to in other British Standards unless different limits are prescribed.

(5.1) Functional Tests[20]

Realistic functional tests rather than a somewhat arbitrary chemical classification should enable newer insulating materials to be used to full advantage. Such tests need to be accelerated, to enable a reasonable prediction of performance over twenty or thirty years to be obtained in, say, two or three years. The most reliable method appears to be to test actual apparatus, models or materials at a series of elevated temperatures, choosing some important aspect of physical deterioration as an end point.

Arrhenius established that chemical reaction rates vary with temperature according to the equation

$$\text{Rate} = A_0\varepsilon^{-E/RT} = A_0\varepsilon^{B_0/T} \quad . \quad . \quad . \quad . \quad (5)$$

where E is the activation energy for the reaction, R is the gas constant per gramme molecular weight and T is the absolute temperature.[21] For a particular reaction, E and R can be combined in the constant B_0, and several investigators have shown that such a law governs the thermal degradation of insulating materials over particular temperature ranges.[22] This can be expressed in the form

$$\log L = A + B/T \quad . \quad . \quad . \quad . \quad . \quad (6)$$

By testing at a series of elevated temperatures and plotting logarithm of life, L, against the reciprocal of T, an approximately straight-line graph is obtained if one type of polymer degradation is predominant throughout the temperature range. Finding the most accurate true line by regression analysis,[23] and extrapolation, may allow a reasonable estimate to be obtained of insulation life at lower temperatures. Comparison of such tests with field experience for long-established insulation has shown good agreement, and, consequently, accelerated life testing has been used extensively to evaluate newer insulating materials. While this technique must be used with great care, its development and agreed use should lead to fuller utilization of all types of insulation.

Much published work in this field has been carried out in the United States. Apart from development to establish specifications for insulating material performance,[24] models have been proposed for use in motor[25] and transformer[26] design which are intended to simulate the important features of complete apparatus and thus enable the performance of a combination of insulating materials to be assessed.

Pending further development and possible adoption of such test methods, recent general practice has been to specify fairly conservative temperature limits for most insulation classes in standards relating to actual equipment, with full regard for adverse conditions such as vibration and differential expansion which must always be considered together with thermal ageing.[27]

(6) CONSTRUCTION AND APPLICATION OF SILICONE-INSULATED EQUIPMENT

(6.1) Conductors

Glass-covered conductors treated with organic-modified silicone resins have good abrasion resistance, are suitable for Class H machine windings, and are also used frequently with Class B or Class F impregnating varnishes. A combination of glass and polyester fibres has been used as an alternative to glass, particularly in the United States. For long-term operation at temperatures above 180° C, glass-covered conductors treated with unmodified silicone resins are preferred.

Many silicone-insulated dry-type transformers are wound with

asbestos-paper lapped conductors, from which most of the organic sizing is removed by baking the coils at 200° C for several hours before impregnation in silicone varnish. In the United States, conductors with two-ply insulation of asbestos and glass are commonly used.

Conductors coated with enamels based on either organic-modified silicone or polyester resins attain maximum thermal endurance after impregnation in silicone varnish.[16, 17]

(6.2) Cables

The principal applications for silicone-rubber-insulated cables are in aircraft and naval vessels, where their cost is justified because copper weight is reduced and a residue of silica remains to insulate and support the conductors after prolonged exposure to flames. Outer insulation, based on asbestos, polytetrafluorethylene or polyester[28] materials, is often added to improve handling characteristics or solvent resistance (see Fig. 5). In some cases, notably a new mining telephone cable and one design of high-temperature aircraft cable, silicone-varnished glass-fibre insulation is used instead of silicone rubber.

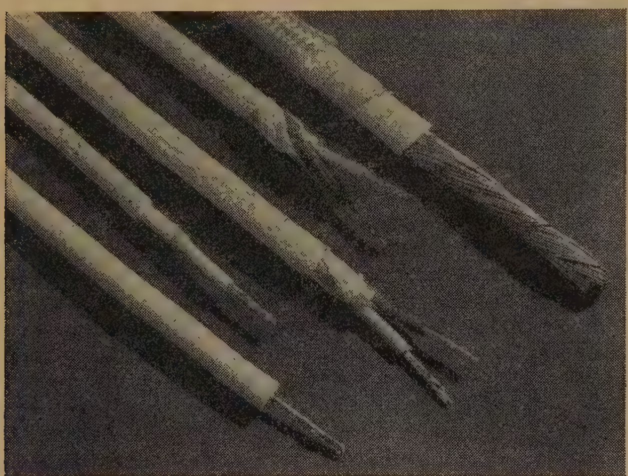


Fig. 5.—Silicone-rubber cables.

From top to bottom:
1 and 2. Silicone-rubber-insulated, asbestos roved. Glass braided overall with silicone-varnish finish.
3 and 4. Silicone-rubber-insulated, asbestos roved. Asbestos braided overall.
5. Silicone-rubber-insulated ignition flex.

Industrial applications of silicone-insulated cables include flexible wiring near ovens and furnaces, where operation at high ambient temperatures is required.

(6.3) Rotating Machines

In this field,[29] probably the most important current design trend with silicone insulation is towards replacing Class B materials in motors subjected to intermittent heavy overloads. Traction motors[30–32] and mill motors are important examples, and many made in the United States and Britain are fully or partially insulated with Class H materials.

Class H insulation is used in machines which operate at high ambient temperatures, including some industrial fan motors, and in auxiliary equipment for nuclear reactors where the good radiation resistance of silicone resins is also advantageous.[33]

A high power/weight ratio can be achieved with suitable design and increased working temperature, and is particularly valuable for aircraft motors and generators. There is some interest in using silicones for this purpose in other types of machine,[34] but the advantages are usually less apparent, as shown in an analysis by Kallas, in 1955, of the applications of two thousand silicone-insulated induction motors made by a manufacturer in West Germany.[35] Only 4·8% were normally loaded to full Class H rating, whereas 47% were used at high ambient temperatures and 22% were used in applications with high switching frequencies.

(6.3.1) Construction.

The first silicone-insulated machines only differed from their Class B equivalents in that silicone resins replaced organic resins for mica bonding, glass cloth or asbestos coating and for final impregnation.[13] This type of construction is probably still the most suitable where maximum thermal endurance is required, but many designs have evolved differently. Silicone rubbers are suitable for novel design and production techniques, and have been used to an increasing extent as a replacement for resinous insulation, in Class B, F and H machines. One notable application in the United States is the outer taping of field coils for traction motors with glass-reinforced partly-cured silicone-rubber tape. Curing by heat and pressure forms a resilient, waterproof outer jacket. Similar insulation has been used on field coils and armatures of some traction motors made in Britain.[31]

Unreinforced silicone rubber is used to insulate stators on induction motors which have now been in production for over four years in the United States, with outputs up to 4 000 h.p. and voltages up to 6 600 volts.[36] The end windings are protected by an outer taping of alkyd-varnished glass cloth, and the overall insulation is rated Class B. A major application has been in contaminated atmospheres when flameproof equipment is not required, as a cheaper alternative to totally-enclosed fan-cooled motors.

The recently developed self-adhering silicone-rubber tapes, described in Section 3.3, can be used without pressure or heat in many applications. This simplifies manufacturing methods, and should make these materials attractive for machine winding insulation. They are already used in the United States for taping phase connections on large rotating machines after assembly, and for similar applications.

Many machines contain both silicone and organic materials, including Class H conductors and adjacent insulation for maximum local thermal endurance, with impregnation in an organic varnish to give improved physical properties or to simplify manufacturing procedure.

(6.3.2) Design Limitations.

Machines larger than about 5 000 kVA may be unsuitable for operation above Class B temperature limits because of differential expansion between copper and iron,[27] but to allow for localized heating or accidental overloading, some high-temperature insulation is often justified. Glass-covered conductors treated with alkyd-modified silicone resins are used in some turbo-generator stators made in Britain, and in the U.S.S.R. turbo-generator rotors rated up to 150 000 kVA are insulated with silicone resin-bonded glass cloth and mica-glass cloth.[37]

Bearing difficulties can occur at high temperatures. Silicone or other high-temperature lubricants are used when necessary, particularly for machines operating at high ambient temperatures.

Excessive brushwear can occur in totally-enclosed silicone-insulated machines operating continuously at high temperatures. Small quantities of volatile siloxanes are evolved, and may reach sufficient concentration for a thin, abrasive layer of silica to be formed in the brush contact arc.[38, 39] Remedies include baking the windings at about 250° C after impregnation to remove volatiles, and excluding silicone rubbers, which generally evolve more volatiles than the resins. Brushes having high resistance to abrasive wear are also useful.

(6.4) Transformers

Dry-type distribution transformers[40–42] can be installed at load centres where oil-filled units are prohibited because of fire risk. Applications occur in mining[43] and industry; other suitable sites are the basements of large buildings, or vaults beneath pavements.

Class H and Class C insulation is now used for most dry-type distribution transformers, to permit high hot-spot temperatures so that overall dimensions can be kept close to those of oil-filled units without needing forced-air ventilation. There is a considerable weight reduction compared with liquid-cooled transformers, and some saving in floor space since no cooling tubes are needed.

Small transformers, particularly for aircraft use, are insulated with silicones, mainly to reduce weight. Cooling is by air or by silicone fluid.[44]

A range of welding transformers with silicone insulation is manufactured in Denmark, and other transformers of similar construction have been used in the United States and Britain for lighting supplies and miscellaneous applications.[47]

(6.4.1) Construction.[40, 41, 45]

For most purposes ventilated units are satisfactory, but sealed units, usually containing nitrogen at slightly above atmospheric pressure, are preferred in highly contaminated atmospheres.

Radial and axial spacers, in the cooling ducts, are often made from porcelain, glass-bonded mica or other inorganic materials. Silicone-resin-bonded glass-cloth laminate is sometimes used, and is less fragile but more expensive. Where voltage stresses are not high, e.g. on the l.v. side and some sections of the 11 kV side in a typical 11 kV/440-volt transformer, silicone-resin-impregnated cement-asbestos board may be used.

Several constructions have been adopted for h.v./l.v. barrier insulation. High material and manufacturing costs have limited the use of silicone-resin-bonded glass-cloth-laminate tubes, which are the nearest equivalent to the familiar phenolic-resin-bonded paper-laminate cylinders of Class A transformers. Instead, some British and United States manufacturers have substituted wraps of silicone-varnished glass cloth, or alternate layers of this material and silicone-rubber-coated glass cloth.[40, 41] Layers of asbestos paper or silicone-resin-bonded mica-glass cloth have also been used.

Asbestos paper is often used for interlayer insulation, and asbestos millboard is sometimes used for core tubes and l.v. winding end wedges. Phase insulation often consists of sheets of silicone-resin-bonded glass-cloth laminates.

The complete windings are normally vacuum impregnated in silicone varnish, with a second dip impregnation to give adequate resin build and a smooth finish.

(6.4.2) Operating Characteristics.

Silicone-insulated dry-type and oil-filled transformers can have comparable efficiencies. For example, the efficiency of one manufacturer's dry-type transformers of 750 kVA, 11 kV rating is given as 98·27% measured at 150° C, compared with 98·43% measured at 75° C for an oil-filled unit of similar rating.[40] A design of silicone-insulated mining transformer is expected to have losses and regulation similar to a conventional oil-filled transformer.[46]

The absence of liquid cooling results in a high temperature gradient along the winding, and in ventilated units the winding hottest spot at full load may be 100° C above the temperature at the base. To ensure the most economical and compact design, many British and United States manufacturers favour a maximum temperature of 210–220° C, which is permissible with a combination of inorganic materials and suitable silicone resins in accordance with a subsidiary clause of Class C, B.S. 2757.

Most dry-type distribution transformers built to date have been in the 300–1 000 kVA range, though larger units up to 4 000 kVA have been built.[40] Their low impulse level has limited the working voltage to a maximum of 15 kV, but recently high-voltage silicone-insulated transformers, filled with perfluoropropane gas (C_3F_8), have been built in the United States, and Manning has predicted that this construction should achieve wide use over the next decade at voltages up to 65 kV.[48]

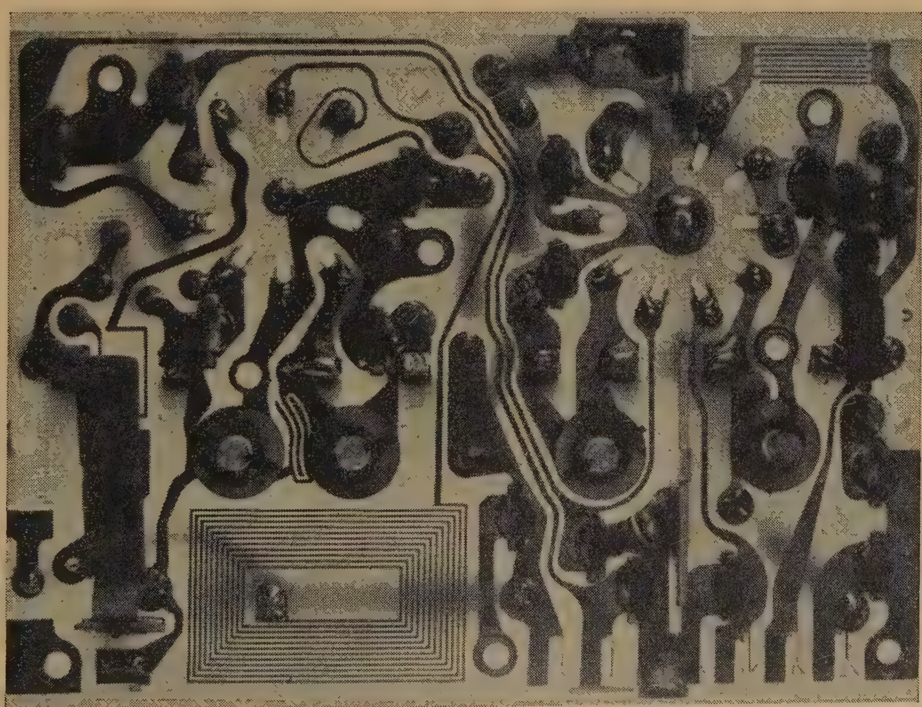


Fig. 6.—Television-receiver tuning unit: printed coil and capacitor on a silicone-laminate base.

(6.5) Applications in Electronic Equipment

Because of their stable electrical characteristics, with varying temperature and frequency, silicone materials are often used in electronic equipment operating at 100° C or less, where high thermal endurance is consequently not essential.

Silicone-resin glass-cloth laminates are used for coil formers, printed-circuit bases and similar applications in airborne equipment. For some purposes, the appreciable percentage drift of power factor with varying humidity is a disadvantage.

(6.5.1) Printed Circuits.

The development of printed circuits based on silicone laminates has been retarded by difficulties in bonding the material to copper foil. Thin layers of phenolic or epoxy adhesive give adequate peel strength, but are generally unsuitable where very stable surface electrical characteristics are required, as for printed coils and capacitors. Recent development has enabled silicone adhesives with favourable electrical characteristics to be used, and a recently-designed television-receiver tuning unit contains printed components of this type (Fig. 6). The silicone laminates and adhesives have a zero or slightly negative temperature coefficient of permittivity, as illustrated for dimethyl silicone fluids in Fig. 1, giving greater capacitance stability than is obtainable from other types of laminate base. Material and processing costs of such units are justified by the saving in labour costs and better reproducibility of the printed components, compared with conventional designs.

(6.5.2) Capacitors.

Silicone fluids have been used in some plastic-film capacitors because of their electrical characteristics and chemical inertness; by lubricating the film during winding and by filling voids the capacitance and electric strength are increased.[50] Silicone-rubber gaskets and terminal insulation are used in capacitors containing chlorinated dielectrics, because of their resistance to these materials.

(6.5.3) Resistors.

Fine-wire voltage-dropping resistors, of the type commonly used in television receivers, are often encapsulated in a cement based on silicone resins which can be cured at temperatures not greater than 250° C.

Though the material cost per resistor is higher than for vitreous enamelling, there are fewer rejects due to oxidation of the wire, and this results in an overall saving.

(6.6) Insulator Treatments

Various silicone treatments have been used to prevent surface-moisture formation. Baked-on silicone fluids or air-drying silicone resins are sometimes applied before installation, or silicone greases may be applied afterwards and, if necessary, during periodic maintenance.

(6.7) Industrial and Domestic Heating Appliances

Silicone-resin glass-cloth laminates are used in the construction of dielectric heating equipment,[51] because of their heat resistance and low power factor. Thermostat control units and similar components often contain silicone insulation.

Silicone-rubber or resin-coated glass sleeving is used to insulate leads in domestic irons and other appliances, and silicone-rubber-insulated cable is used for heater wiring in some washing machines. Silicone-resin glass-cloth laminate is used for element supports in some convector heaters.

Mineral-insulated heating elements and cables are often sealed against moisture by treatment of the lead entry with silicone resins.

(6.8) Illumination

Some instant-start fluorescent lighting tubes are silicone coated to prevent the formation of a surface-moisture film which impairs starting characteristics.[52] Silicone-resin-based cements are used to seal terminal caps of high-temperature electric light bulbs to the glass envelope.

(7) ECONOMIC ASPECTS

Class H insulation often directly replaces Class B, and Table 4 gives representative price ratios. These costs are very similar in Britain and the United States.

Insulation cost is only a small fraction of the total in much electrical equipment, and silicone materials often enable compensating savings in design or manufacture to be achieved, or confer a marked improvement in reliability for a small increase in price. These factors account for the use of silicone insulation in some domestic appliances and similar apparatus where overall costs must be kept low. In other cases, expensive electrical equipment is justified, as typified by the use of silicone-insulated apparatus in aircraft, where it has been reported that a reduction of 1 lb in weight may save £15 per annum in operational costs.[53]

(7.1) Insulation Costs of Rotating Machines

The replacement of Class B with Class H insulation in small machines can increase cost appreciably, as shown in Table 5. The effect is less marked in larger machines, where insulation costs are proportionally lower. Some British mill motors with partial silicone insulation have been sold at normal Class B prices, but this has not been possible for full Class H machines, which are invariably more expensive than those with Class B insulation and of similar frame size.

Table 4

Representative Insulation Cost Indices

	Class B	Class H	Cost index, Class H/Class B
Resin-glass cloth laminates, $\frac{1}{16}$ in thick	Phenolic resin	Silicone resin	2
Varnished glass cloth, 7 mils thick ..	Organic resin	Silicone resin	2·2
Glass cloth tapes (5 mils thick, 1 in wide)	Organic resin	Silicone rubber	2·3
Slot insulation (glass/2 layers mica/glass), 12 mils thick	Organic resin	Silicone resin	1·3
Sleeving (2 mm bore, 0·5 mm thick) ..	Organic varnished glass cloth (rolled)	Extruded unreinforced silicone rubber	0·88
Glass-covered conductors, 13 s.w.g. ..	Organic varnish	Silicone or modified silicone varnish	1·07
Impregnating varnish	Oil-modified phenolic or alkyd	Silicone	5

Table 5

APPROXIMATE INSULATION COST INDICES FOR 440 VOLT 3 H.P. 3-PHASE SQUIRREL-CAGE INDUCTION MOTOR

	Class B	Class H
Glass-covered conductors	0·66	0·71
Slot wedges	0·08	0·16
Slot liners	0·08	0·14
Phase insulation	0·03	0·04
Impregnating varnish (double dip) ..	0·15	0·75
Total cost of insulation and conductors	1·0	1·8

Examples of induction motor costs in Germany in 1955 have been given by Kallas.[35] A 0·75 kW Class H machine was 67% dearer than a Class E machine of similar rating and frame size. A 300 kW Class H motor was 27% dearer than a Class B insulated machine of similar frame size rated at 240 kW, giving a very similar cost per kilowatt. For higher-voltage machines, the cost per kilowatt proved to be lower for Class H machines; a high-voltage 300 kW Class B induction motor was 16% more expensive than a Class H motor of similar output and efficiency but smaller frame size.

In 1950, Henry reviewed Class H and Class A rewind costs of a rewinding firm in the United States, for induction motors in the range 2–60 h.p.[54] Overall costs for a Class H rewind were 50% to 200% higher than for Class A, mainly owing to higher material costs, but also to higher direct labour costs which largely apply to rewinding with either Class B or Class H materials The smallest percentage increase was on the larger machines.

In the United States the increasing use in Class B machines of silicone-rubber insulation, which is generally easier to apply than mica-glass materials, has enabled appreciable savings in manufacturing costs to be obtained in some cases. These can offset the higher material costs of silicone-rubber tape, which is about 30% dearer on a volume basis than Class B mica-glass. The newly-developed self-bonding tapes described in Section 3.3 should help further in this respect.

(7.2) Transformer Costs

Dry-type silicone-insulated transformers manufactured in Britain have generally been 1·3–1·8 times as expensive as equally-rated oil-filled Class A units.[40] Manning has quoted the price ratio in the United States as 1·25 for 150° C temperature-rise ventilated units, and 1·5 for 150° C temperature-rise units sealed in nitrogen.[48]

Costs of particular sections of the insulation vary considerably in different designs. Some constructions have relatively little silicone content prior to final impregnation in silicone varnish, which, in the form of absorbed resin, may comprise about 5% of the final cost, but the substitution of inorganic for organic materials increases costs appreciably.

The use of such transformers is justified when an overall saving in installation costs can be obtained. For example, a 500 kVA installation beneath the pavement in a Glasgow street was £1 000 cheaper than a separate substation with an oil-filled unit.[55]

(8) FUTURE DEVELOPMENTS

The trends discussed are likely to continue, with silicone resins replacing organic resins in much equipment which is currently Class B insulated, and with the increasing use of silicone rubber in the form of cable, sleeving and tapes. Designs are likely to continue to evolve by stages, with partial silicone insulation as in interim measure in some cases. Replacement of Class A or Class E insulation in most applications is unlikely, for silicones will probably remain relatively expensive to produce.

In some cases, development of new silicone products with easier processing characteristics should help to reduce manufacturing costs of insulation components. Desirable improvements would include reductions in the curing time and temperature needed to develop optimum properties in silicone rubbers, a reduction in curing temperatures of the resins and simplification of laminate processing.

Research is also directed towards a further improvement in physical properties. For most purposes the electrical characteristics are satisfactory, but further improvements are sought in the tensile and tear strength of silicone rubbers, in the bond strength of some silicone resins and in adhesives for bonding copper foil to silicone laminates.

(9) ACKNOWLEDGMENTS

The author wishes to thank British Insulated Callender's Cables Ltd., and Sydney Bird Ltd., for permission to reproduce Figs. 5 and 6. Thanks are also due to Dow Corning Corporation for American data, and to many manufacturers of electrical insulation and equipment who have supplied information.

(10) BIBLIOGRAPHY

(1) BAKER, C. J.: 'Silicone Elastomers', *Research*, 1953, **6**, p. 458.

(2) KIPPING, F. S.: 'Organic Derivatives of Silicon', *Proceedings of the Royal Society*, 1937, **159**A, p. 193.

(3) BASS, S. L.: 'Silicones—New Engineering Materials', *Chemistry and Industry*, April 5th and 12th, 1947, p. 171 and p. 189.

(4) WARWICK, E. L., HUNTER, M. J., and BARRY, A. J.: 'Polymer Chemistry of the Linear Siloxanes', *Industrial and Engineering Chemistry* (Industrial), 1952, **44**, p. 2196.

(5) HARTSHORN, L., PARRY, J. V. L., and RUSHTON, E.: 'The Dielectric Losses in Some Representative Insulating Materials', *Proceedings I.E.E.*, Paper No. 1451 M, February, 1953 (**100**, Part IIA, p. 23).

(6) RUSHTON, E., and RUSSELL, G.: 'The Dielectric Properties of Silicone Rubbers', E.R.A. Report Ref. L/T325.

(7) SERVAIS, P. C., and RILEY, I. H.: 'Silicone Rubber—Its Growth and Recent Development', *Rubber and Plastics Age*, 1957, **38**, p. 600.

(8) NOBLE, M. G., and LUPFER, D. A.: 'Tailoring of Silicone Rubber to meet Electrical Requirements', *Rubber World*, **131**, p. 71.

(9) BLOW, C. M., and COX, R. C.: 'Silicone Rubbers Today', *Rubber Journal and International Plastics*, 1957, **133**, p. 738.

(10) WARWICK, E. L.: 'Effects of Radiation on Organopolysiloxanes', *Industrial and Engineering Chemistry*, 1955, **47**, p. 2388.

(11) BURNISTON, R. L.: 'Silicone Elastomers', *Electrical Review*, 1954, **155**, p. 753.

(12) HAWTHORN, A. N., and MESSENT, S. W.: 'The Properties of Some of the Newer Laminated Plastic Insulating Materials', *Proceedings I.E.E.*, Paper No. 1495 M, March, 1953 (**100**, Part IIA, p. 190).

(13) GRANT, G., KAUPPI, T. A., MOSES, G. L., and GIBSON, G. P.: 'Motor Tests Evaluate Thermal Endurance of Class H Insulation and Silicone Varnish', *Transactions of the American I.E.E.*, 1949, **68**, p. 113.

(14) RENWICK, W. J., and REED, J. R.: 'Silicone Resins, Fluids and Elastomers in Insulation for Use at Power Frequencies', *Proceedings I.E.E.*, Paper No. 1442 M, January, 1953 (**100** Part IIA, p. 239).

(15) McLoughlin, J. R.: 'The Mechanical Properties of Silicone Resins', *Insulation*, 1956, **2**, p. 28.
(16) Dexter, J. F.: 'Thermal Evaluation of Enamelled Magnet Wire', *Transactions of the American I.E.E.*, 1956, **75**, Part III, p. 40.
(17) Snadow, R., and Smith, D. G.: 'A New Enamelled Wire', *BTH Activities*, 1957, **28**, p. 201.
(18) Collinson, H. A., and McDowall, R.: 'Silicone, Melamine and Furane Resins', *Glass Reinforced Plastics* (Iliffe and Sons, Ltd., 1954).
(19) 'General Principles upon which Temperature Limits are Based in the Rating of Electrical Machines and Apparatus', American I.E.E. Standards, No. 1, June, 1947.
(20) Berberich, L. J., and Dakin, T. W.: 'Guiding Principles in the Thermal Evaluation of Electrical Insulation', *Transactions of the American I.E.E.*, Paper No. 56–248.
(21) Glasstone, S.: 'Textbook of Physical Chemistry' (Macmillan and Co., Ltd., 1948).
(22) Dakin, T. W.: 'Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon', *Transactions of the American I.E.E.*, 1948, **67**, Part I, p. 113.
(23) Davies, O. L.: 'Statistical Methods in Research and Production' (Oliver and Boyd, 1957).
(24) 'Proposed Test Procedure for Evaluation of the Thermal Stability of Enamelled Wire', American I.E.E. Standard No. 57, October, 1955.
(25) 'Proposed Test Procedure for Evaluation of Systems of Insulating Materials for Electric Machinery Employing Form-Wound Pre-Insulated Coils', American I.E.E. Standard No. 511, October, 1956.
(26) 'Proposed Test Procedure for Evaluation of Ventilated Dry-Type Power and Distribution Transformers', American I.E.E. Standard No. 65, November, 1956.
(27) 'The Electrical Performance of Rotating Electrical Machinery', B.S. 2613: 1957.
(28) British Patent No. 743396.
(29) Davis, J. H.: 'Silicone Insulated Motors', *Electrical Review*, 1958, **162**, p. 709.
(30) 'Railway Electrification Contracts', *ibid.*, 1957, **160**, p. 135.
(31) 'Silicone Insulated Traction Motors', *ibid.*, 1958, **162**, No. 15, p. 703.
(32) Grant, G., Kauppi, T. A., Moses, G. L.: 'Investigation of Silicone Insulation on High Temperature Railway Motor', *Transactions of the American I.E.E.*, 1947, **66**, p. 305.
(33) 'Calder Hall Engineering Elements', *Engineering*, 1956, **182**, p. 469.
(34) 'New Alternator Design', *Electrical Journal*, 1956, **156**, No. 17.
(35) Kallas, H.: 'Fünfjähriger Einsatz der Siliconisolation im Elektromaschinenbau', *Die Electro-Post*, 1955, **8**, p. 221.
(36) Kuehlthau, J. L., and Kryder, P. A.: 'Silco-Flex Insulation Opening Way to Longer Motor Life', *Allis-Chalmers Electrical Review*, 1955, **20**, p. 4.
(37) Andrianov, K. A., and Kalitvianskii, V. I.: 'The Use of Silicone Insulation in Electrical Engineering', *Elecktrichestvo*, 1955, **4**, p. 62.
(38) Marsden, J., and Savage, R. H.: 'Effects of Silicone Vapor on Brush Wear', *Transactions of the American I.E.E.*, 1948, **67**, Part II, p. 1084.
(39) Campbell, H. E., Lundy, R. T., and Snyder, J. D.: 'A Brush Manufacturer looks at Silicone Insulation', American I.E.E. Conference Paper 58–205.
(40) 'Dry-Type Transformers', *Electrical Journal*, 17th February, 1956.
(41) Manning, M. L.: 'The Application of Class H Insulation to Transformers', *Transactions of the American I.E.E.*, 1951, **70**, Part II, p. 1427.
(42) Brown, W. L.: 'Dry-Type Transformers', *Electrical Times*, 1958, **134**, p. 297.
(43) Norris, E. T.: 'Transformers, Regulators and Reactors', *Proceedings I.E.E.*, Paper No. 2611, June, 1958 (**105A**, p. 241).
(44) Langley, Morris, A.: 'Small Power Transformers for Aircraft Electrical Equipment', *Proceedings I.E.E.*, Paper No. 800 U, January, 1949 (**96**, Part III, p. 279).
(45) Terry, W. M.: 'Performance Characteristics of 150 C Rise Dry-Type Transformers', *Allis-Chalmers Electrical Review*, 1955, **20**, p. 10.
(46) 'Dry Type Transformers in Pits', *The Times Review of Industry*, May, 1958.
(47) Dexter, J. F., Manning, M. L., and Walker, H. P.: 'Low Voltage, Air Cooled Transformers Designed for 225 C Operation', *Electrical World*, 1948, **130**, p. 97.
(48) Manning, M. L.: 'Silicone Insulation—Its Usage and Future for Power Transformers', *Insulation*, June, 1958, p. 18.
(49) Hayden, J. D., and Hayward, B. F. W.: 'Silicone Insulants', *Electronic Engineering*, 1956, **28**, p. 58 and p. 115.
(50) British Patent No. 787342.
(51) 'Phenolic/Paper and Silicone/Glass Laminate in R.F. Heating Equipment', *British Plastics*, 1956, **29**, p. 368.
(52) Brittain, G. D.: 'Silicone Treated Fluorescent Tubes', *Electrical Review*, 1955, **156**, p. 580.
(53) Follett, S. F.: 'Electrical Equipment in Aircraft: Survey of Past and Present Practice and Future Trends in Design', *Proceedings I.E.E.*, Paper No. 2062 U, April, 1956 (**103A**, Supplement No. 1, p. 4).
(54) Henry, W.: 'Silicone Rewind Costs', *Electrical Construction and Maintenance*, December, 1950, **49**, p. 48.
(55) *Glasgow Herald*, November 20th, 1957.

DISCUSSION BEFORE A JOINT MEETING OF THE MEASUREMENT AND CONTROL SECTION AND THE UTILIZATION SECTION, 6TH JANUARY, 1959

Mr. S. W. Messent: Silicone resins are comparatively new and they still cause a certain amount of difficulty in handling them. Are silicones susceptible to contaminants? I have in mind possible effects on the resins of the material of the tanks or containers and the purity of the commercial solvents which may be employed. Have they any effect on the properties of the resin in the end-product? It is remarked in the paper that heat treatment of a silicone resin reduces any subsequent effect of a solvent. I have not found this to be markedly so, and think it should be emphasized that any contact of silicone insulation with an impregnating varnish should be brief.

I am intrigued with the characteristic curves for laminates given in Fig. 2. On what are the electric-strength curves based? Is it a rapidly applied breakdown voltage or a 1-min value, with the sample immersed in oil or in air? Both electrical and mechanical figures seem to be optimistic.

There is now available in this country a range of insulating materials based upon a mica paper. The mica paper can be impregnated with a silicone resin, and with a reinforcement of glass fabric, for example, is used for a slot or coil insulation. Apart from its high electric strength, this insulation has the advantage of considerable thickness accuracy. With an appropriate type of silicone resin, commutator segment separators and V-rings can be produced.

Finally, on the question of future development the author states that improved adhesives are becoming available. I should like to plead this cause, because I feel that at the moment it is a family weakness. It is often desirable for cost or other reasons to build up an assembly, and the silicone-type adhesives available are not very good. This also applies to the bonding of copper foil to silicone glass sheet for the production of etched circuits.

Mr. W. J. Renwick: For some ten years and more the electrical industry has been experimenting with and using silicone insulating materials. It now seems that, as and when occasions arise which justify their cost, they will be used—for example, where great reliability under severe conditions of temperature and mechanical loading is essential, as in electric traction, particularly on main-line railways. As illustrating this trend I may say that my company is making silicone-insulated traction motors, using inorganic materials, silicone resins and silicone elastomer.

On the subject of excessive brush wear in totally-enclosed silicone-insulated motors operating continuously at high temperatures, can the author indicate the order of temperature he has in mind? Does the phenomenon occur at class-B temperature or even lower? In the absence of such information, users are obliged to carry out their own experimental work.

Can cold-curing silicone rubbers used with catalysts be made to fill large gaps, e.g. those in lifting magnets?

Again, in the matter of silicone-resin-bonded glass-insulated conductors, is it incumbent on the customer to specify the varnish to be used in order to ensure a fully silicone bond?

On the subject of dry-type distribution transformers with class-H and class-C insulation, Fig. A shows the essential con-

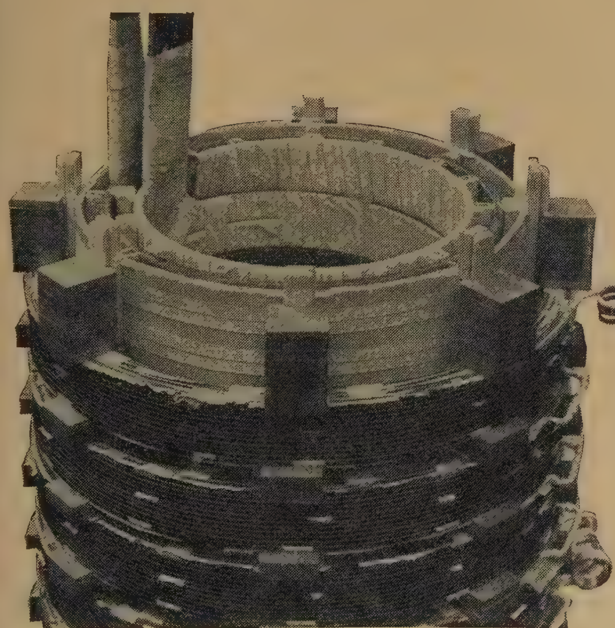


Fig. A.— One limb of class C transformer.

struction of one limb of a class-C 3-phase 550 kVA 11 kV/433-volt ventilated transformer. The insulation between the core and l.v. winding and between l.v. and h.v. windings is in formable silicone-resin-bonded glass sheet and silicone-elastomer-treated glass cloth. Axial spacers, in the cooling ducts, are in rigid silicone-resin-bonded glass fabric. Glass-bonded mica blocks space the disc coils of the h.v. winding. The conductors are insulated with silicone-resin-bonded glass fibre. Final impregnation of the windings is achieved by two immersions in an all-silicone varnish.

Mr. D. B. McKenzie: It is very remarkable that the original silicone work started by Berzelius, who lived from 1779 to 1848, has lain dormant for so many years. We at the Royal Aircraft Establishment were probably among the first users to appreciate the value of silicones for operating equipment at higher temperatures and so reducing the weight. We were also aware of its peculiar moisture resistant properties. Over 16 years ago, in May, 1942, it was reported that methyl silicon chloride, when diluted in a volatile solvent, sprayed on to a phenolic paper board and dried, improved the surface resistivity by a factor of about 50. Unfortunately the result was not permanent. In December, 1943, a silicone-based ignition sealing-compound of American origin was brought to our notice for filling aircraft-engine ignition harnesses as a moisture seal. It was promising for this purpose, but the Service was not prepared to sacrifice the increased weight of the harness and preferred a well-sealed unit. The first practical application of silicone rubber for aircraft electrical use was on cables, and development started at the end of 1947. This rubber was weak mechanically and had to be protected against contamination from kerosene. This was achieved by an asbestos roving and a silicone-varnish-bonded glass braid. In about 1955 the asbestos roving was replaced by a polyester tape, giving a smaller and lighter cable which was resistant to the liquids encountered in a modern aircraft.

Is there any possibility of getting a fluorinated silicone rubber which can be extruded and which also has mechanical properties capable of withstanding the normal installation handling encountered on aircraft?

Dr. J. H. Mason: Although the thermal characteristics of silicone insulation are their chief merit, I was disappointed to find little reference to their electrical properties. It would be interesting to know how the filler content in silicone rubbers, and the resin content in silicone-glass laminates, affects the electrical and mechanical properties.

In Section 5.1 the author mentions that vibration and differential thermal expansion affect thermal ageing, and I suggest that the effects of electrical discharges also be considered. Provided that silicone rubber is not subject to mechanical tension or flexing, it has excellent resistance to discharges both at 20° and 150° C, as shown in Table A, where it is compared with synthetic-resin-bonded-paper laminate. Some samples of silicone rubber failed sooner at 20° C than at 150° C, presumably owing to local inhomogeneities. If after 1 000-hour tests the silicone-rubber sheets are folded, areas subjected both to discharges and to 150° C crack when folded through about 300°, whereas areas which have been subjected only to discharges at 20° C, or only to heating at 150° C, must be creased together before cracking occurs. The author mentions in Section 3.1 that the addition of ferric oxide improves certain properties of silicone rubber, and we find that silicone rubber containing ferric oxide is less liable to crack after ageing by heat and discharges than rubbers which contain only a silica filler.

Table A also shows that some samples of silicone-impregnated glass laminate have much greater resistance to discharges than others. Laminates Nos. 2103 and 2104 both failed instantaneously when only 30 kV/cm was applied at 150° C or 50 kV/cm at 20° C, whereas laminate No. 2105 survived over 200 hours at 140 kV/cm at 150° C. Microscopic examination shows that laminate 2105 has a more uniform structure than the others, and I wonder whether higher electric strength of laminates impregnated with phenyl-containing resins (mentioned in Section 4.2) is due to better and more uniform mechanical bond between these resins and glass than with other resins.

Table A

Discharge Resistance of Silicone Rubber and Silicone Glass Laminates compared with that of S.R.B.P. Laminate.

Material	Temperature	Stress (r.m.s.)	Life at 500 c/s
	deg. C	kV/cm	hours
Silicone rubbers S.80	20	130	319 and >370
	150	180	>1 000
S.152 (+ ferric oxide)	20	120	50 and >370
	150	180	>1 000
Silicone glass laminates† Resin / Pressure: lb/in²			
MS 2105 / 500	150	140	210, 220
		180	21, 220
2104 / 20	150	30	Instantaneous
2103 / 1 000	150	30	Instantaneous
S.R.B.P.* electrical grade	20	140	2·5
	20	80	92 ± 15
	105	50	74 ± 21

* These samples were 1·6 mm thick and were tested at 50 c/s; all other samples were about 1 mm thick and tested at 500 c/s.
† Laminating pressure applied for 30 min at 175° C; laminates then part-cured for 16 hours at 90° C, and finally for 2 hours at 200° C.

In Section 4.2 it might have been mentioned that borosilicate glass-fibre is preferable to soda glass, since the latter may suffer electrochemical attack when subject to heat and moisture. Finally, is the use of silicone rubber gaskets limited by mechanical set after temperature cycling, and by the comparatively high gas and moisture permeability of silicone rubbers?

Mr. E. Jones: Silicone resins are unusually solvent-retentive; while solvent is retained, curing is inhibited and the electric strength is low. Can one not use solvents which are more readily removed than toluene and xylene? Silicone-resin-treated mica-paper more readily gives solid mouldings of high electric strength; the high permeability of the paper probably assists solvent evaporation.

The performance of silicone-treated asbestos-cement boards in high-humidity conditions is, in my experience, disappointing, considering the cost of treatment.

Is 'alkyd-modified silicone' a fair description of varnishes of low silicone content? 'Silicone-modified alkyd' would be more appropriate. These varnishes are only marginally superior to some modern terephthalate varnishes in heat resistance.

In some American 'silicone-insulated' traction motors the silicone was used only as a mica bond; non-silicone varnish was used for impregnation; later, silicone-modified alkyd varnish, of low silicone content, was used. It is vital to distinguish between silicone bonding and silicone insulation. Is the use of silicones technically justified in traction motors? The literature available never discloses the nature of the previous mica bond. For example, the Americans claim that the life of live-roll mill motors (usually insulated to 'traction' standards) is greatly increased by using silicones; out of 3 000 such motors (containing no silicones) made by my company, only two failures have occurred which can reasonably be attributed to the insulation.

Field and stator coils are successful applications for silicone elastomers as a replacement for mica; these elastomers have good heat, discharge and moisture resistance, improved thermal conductivity and ease of application: 6·6 kV stator coils with the same thickness of elastomer as would be used for mica have operated at 12 kV continuously, out of doors, for two years, without detectable change. London Transport Executive have used elastomers on motor windings, and it is hoped that they will publish their service experiences.

The reversion of elastomers at high temperature in the absence of oxygen was once a problem; has this been overcome?

Class-H dry transformers are much more expensive than oil-filled ones, and their use can be justified only where oil is a fire hazard. However, one can ignite silicone-treated glass insulation and also elastomer-insulated cable. True, the silicone reverts to silica, but this is a result of the conflagration.

Finally, I should be interested to know the mechanism employed in self-bonding silicone elastomers.

Mr. R. Snadow: Although there is little or no demand to operate very large rotating machines at class-H temperatures, it is interesting to speculate on the possibility of using silicone rubber to insulate h.v. stator coils by such techniques as extrusion or moulding. It might be possible in this way to supersede the relatively costly taping and wrapping processes now in use, and by applying the whole of the major insulation in one operation, to achieve a covering which was no more expensive, or even cheaper, than at present, in spite of employing a more expensive material.

It is important, of course, that the insulation on coils subjected to high electric stress should be substantially free from voids, or there will be a danger of corona discharges. The manipulation of silicone rubber around h.v. coils should therefore be carried out in such a way as to provide a solid homogeneous envelope adhering strongly to the windings in the final cured form. Even so, the fact that silicone rubber has relatively good resistance to corona would allow it to be used with greater confidence.

The use of a rubbery type of insulation for large machines is attractive because it would minimize the chance of windings being damaged while they are being inserted into stator slots, and would allow movements occurring in service—including those due to short-circuits—to be accommodated with ease.

Possible dangers due to the reversion of silicone rubber to a depolymerized form in certain drastic conditions must be borne in mind, and it would be interesting to learn whether recently introduced modifications of silicone rubber are less prone to exhibit this phenomenon.

Mr. N. Parkman: In many cases silicone rubbers are used in electrical components, not only as insulation, but as a means of maintaining a gastight seal, e.g. a gasket of some sort. The inability of the general range of silicones to maintain such a seal over long periods under conditions of constant deflection, especially at high temperatures, is well known. There have been certain improved grades which have been developed by incorporating small amounts of such materials as cadmium oxide with existing rubber stocks. Would the author comment on the advantages which are gained by employing silicone stocks with vinyl side groups and using ditertiary butyl peroxide as a cross-linking agent?

My next point concerns resistance to hydraulic-type fluids, and such things as jet-engine fuel. We know about the superior resistance of fluorinated compounds already available. Recently we have heard a great deal about the cost of ordinary silicone rubbers, but the cost of the fluorinated ones is very much higher of course. Is there any possibility that the new nitrile silicone rubbers may be at least as good as the fluorinated ones, so far as resistance to fluids is concerned, and perhaps a little less expensive?

It appears to be axiomatic that, in order to achieve the optimum thermal endurance from silicones, whether fluid or solid, one must increase the phenyl/methyl ratio. This seems a pity, because apart from the introduction of the additional polarity, it seems that a bulky phenyl group may well give rise to inferior

mechanical properties, at least in rigid materials. Moreover, the phenyl content of silicones has an important bearing on their resistance to carbon-track formation when the surface is contaminated and the electric stress is applied across it. In general, an increase in phenyl content results in a decrease in the resistance to track formation. For instance, with the international tracking test, methyl rubbers track at about 800 volts, the nature of the track in this case being a very fluffy carbon deposit which can be blown away. The surface is not entirely undamaged, however, because tracking can be induced much more easily than before. On the other hand, the more recent methyl/phenyl moulding resin, usually available with a glass-fibre filler, tracks at about mains voltage under the same conditions.

Mr. S. G. Foord: The original silicones were made by the Grignard reaction, which is essentially an expensive chemical process. With the introduction of the reaction of methyl chloride with silicon, the price should have been reduced sharply, but I do not remember this taking place.

Mr. A. H. Lince (*United States*): What are the properties of the silicone oils, the mould parting agents, in the area of polyethylene stress-cracking activity? Are these properties known, and if so, is there a treatment of the subject in the literature? This subject is of interest to all engineers who are involved in the moulding of polyethylene in long-life products, such as submarine cables. Here, even those materials of manufacture having low levels of stress-cracking activity are dangerous. If there are some sillicones which would qualify under this heading they could be rather attractive.

Mr. P. P. Eckersley: It has been suggested that the heat rise on a transformer, when (presumably) momentarily short-circuited, would be such as to damage it. Surely fuses or circuit-breakers act sufficiently quickly to prevent such a state of affairs.

Mr. J. K. Clark: Can the author give us a little more information on the history of the development of the tensile strength of silicone rubbers between 1944 and 1957 which led to the rather remarkable increase from 450 to 1 500 lb/in^2? Presumably there was some laboratory technique or some other specific approach to the problem of increasing the tensile strength. Was it by altering the molecular structure of the compounds or was it by adding materials, as in the case of increasing the tensile strength of steels?

Some reference has been made already to the plastic and dough-like properties of the silicone rubbers; at a meeting of the London Students' Section of The Institution in 1942 the lecturer demonstrated material which could be manipulated like a piece of putty yet bounced when dropped. Is there any practical application for this truly remarkable material?

Finally, in view of the increasing importance of hydrogen as a medium for cooling large alternators, I should be interested to have some information on the behaviour of silicone insulating materials in this gas.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. J. H. Davis (*in reply*): In reply to Mr. Messent, uncured silicone varnishes should not be in continuous contact with lead, copper or zinc. Welded mild-steel tanks are suitable for storage, and solvents containing organic bases, sulphur or tarry residues should be avoided, but adverse effects are on storage life and curing characteristics rather than the final properties of the cured resins.

The electric-strength curves in Fig. 2 were obtained by increasing the applied voltage uniformly to breakdown in air. Silicones are renowned for their abhesive rather than adhesive properties, but Section 6.5.1 refers to recent improvements.

To answer Mr. Renwick's question on brush wear more fully, further work by motor manufacturers is desirable, but wear is reduced when a machine is only intermittently loaded to class-H temperatures. Little or no increase in brush wear has occurred in totally-enclosed silicone-insulated motors installed at several steelworks.

Large voids can be filled with cold-curing silicone rubbers. Wire coaters normally supply glass-covered conductors coated with either silicone-alkyd or unmodified silicone varnishes, as specified by the customer.

Mr. McKenzie's requirements for an extrudable fluorinated-silicone rubber may possibly be met by adding 5–10% of conventional stock, with little reduction in solvent resistance.

Dr. Mason's interesting results show the high resistance to discharges of silicone rubbers, but I believe that many stocks, not containing small quantities of ferric oxide, would behave as well as the second material in Table A. The different results for silicone-resin laminates indicate the greater freedom from crazing of laminates based on the higher phenyl resin in Table A(MS.2105).

Gaskets made from silicone rubber of low compression set are satisfactory, although their permeability to gases is higher than for natural rubber.

In reply to Mr. Jones, some alcohols, esters and ketones are alternative solvents for silicone resins. Silicone-resin-impregnated cement-asbestos board competes in price with many organic insulation materials, but has much higher heat and arc resistance, making it suitable for many applications. Its electrical properties are admittedly only moderate.

Full or partial silicone insulation is now widely used in traction and steel-mill motors. Case histories show much longer life than was obtained from class-B machines when operating under arduous conditions.

Mr. Jones's work with silicone rubber is valuable, and such techniques as described by Mr. Snadow should facilitate its wider use. In reply to their questions on reversion, or softening, of silicone rubbers, this is still possible with the newer stocks but is a problem only above about 180° C in the complete absence of oxygen. The bonding mechanism of silicone rubber formulations giving self-adhesion is not yet understood.

Section 3.1 deals briefly with Mr. Parkman's first question. The nitrile silicone rubbers are less resistant to aircraft fluids than fluorinated silicone rubber.

Mr. Foord's comment on relative costs of the initial stages in silicone production does not apply to overall manufacturing costs.

In reply to Mr. Lince, prolonged contact with silicone mould release agents can cause stress cracking in low-density polyethylene; high-density polyethylene is much more resistant.

In reply to Mr. Clark, the use of highly reinforcing silica fillers has been a major factor in the development of silicone rubber formulations. No important use, which can be disclosed, has yet been found for silicone 'bouncing putty'. Silicone materials are already used satisfactorily in hydrogen-cooled alternators.

DISCUSSION ON

'THE MEASUREMENT OF HIGH VOLTAGES WITH INDICATING OR RECORDING INSTRUMENTS'*

Mr. R. G. Ackland (*Australia: communicated*): The measurement of the peak values of alternating voltages with undirectional components, only referred to in passing in Mr. Bowdler's paper, is an application with which I have been concerned in the calibration of various types of industrial X-ray equipment. Here one must use a resistance divider, and to keep uncertainties to within 1% or so at, say, 125 kV peak (positive or negative), this divider must have a peak current drain of not more than about 1 mA and a capacitance to earth of not more than about 20 pF. Hence there is practically no alternative to the use of a non-metallic type of divider element. If other calibration facilities for checking the ratio of such a unit are not available, a useful device is a divider made up of a number of, say, 10 or 15 kV elements in series, and a transposition or leap-frog technique, permitting the peak voltage across each one to be measured as it takes its turn at the bottom of the column, with, say, a 15 kV diode-electrostatic-voltmeter combination. In this manner the ratio of the divider can be checked at any time, and to make measurements up to about 150 kV (peak), all one needs as an accurate standard is an ordinary d.c. potentiometer and a 15 kV (peak) wire-wound divider for checking the peak voltmeter. A full description of this technique and of the errors to be allowed for in its use has been published elsewhere.†

Perhaps the most important of these errors is the one, associated with the diode peak voltmeter, which we have called the leakage-conduction error because it is connected with the rate of leakage from the storage condenser of the voltmeter and the associated voltage drop during the charging period due to series resistance in the charging circuit. This is the error to which Mr. Bowdler ascribes the fractional magnitude $1 \cdot 7\,(R_s/R_1)^{2/3}$, where R_s may be defined as the series charging resistance (irrespective of whether it is due to the rectifier or divider or both) and R_1 is the leakage resistance across the storage system. This term should in fact be $2 \cdot 2_3\,(R_s/R_1)^{2/3}$.‡ The discrepancy arises because of the use, in the derivation of the error, of the approximation $\alpha = \sin \alpha$ when α is small. The use of the first- and second-order terms of sine and cosine power-series expansions gives the same result, but the inclusion of the third- and higher-order terms produces the correct figure.

Although the simplified treatment used in deriving this error figure assumes that the ripple in the voltage on the storage condenser C is negligible, this is only done to simplify the determination of the charging period or rectifier conduction angle. Actually, the derivation of the error is based on the fact that there is a loss of charge from the condenser during the non-conducting period; accompanying this there must be some fall in condenser voltage, and there must therefore be an equivalent rise during the charging period. This results in initial and extinction angles (relative to the peak of the charging voltage) which are slightly larger and slightly smaller respectively than the half conduction angle resulting from the simplified treatment, and the mean of the voltages corresponding to these angles is the same as in the simplified case. (The alternative treatment of this error given in Appendix II of the Ackland and Keam paper, in which the initial and extinction angles are derived, confirms that this is so.) The application of an additional correction $\pi/RC\omega$ to allow for the voltage drop on the condenser during the non-conducting period assumes that the leakage-conduction correction only takes into account the difference between the peak voltage being measured and the peak value of the voltage on the storage system. Since in fact the leakage-conduction correction refers to the mean value of the condenser voltage, it is erroneous to apply an additional correction $\pi/RC\omega$ as stated by Mr. Bowdler (and as implied in the footnote on p. 285 of the Ackland and Keam paper).

Mr. G. W. Bowdler (*in reply*): I am indebted to Mr. Ackland for bringing his paper to my notice. The error in my derivation of the leakage-conduction error, to which he refers, has already been dealt with in the corrigenda in Vol. 105, Part A, of the *Proceedings*.

The other point raised by Mr Ackland, namely that the error due to the ripple on the storage condenser should not be added to the calculated leakage-conduction error, is partly covered by the statement at the beginning of the Appendix to the paper that the total error is in general somewhat less than the sum of the errors calculated according to the succeeding paragraphs. The Mathematics Division of the N.P.L. has made an exact computation of the errors of the diode peak voltmeter circuit shown in Fig. 6 of the paper, but ignoring the diode capacitance C_R, for various values of the product $RC\omega$ and the ratio R/R_R. The results are embodied in the following Table, together with, in the last row and column, the values of the errors calculated from the expressions $\pi/RC\omega$ and $2 \cdot 23\,(R_R/R)^{2/3}$.

Ratio R/R_R	Amount by which the steady-state mean voltage on C (Fig. 6 of paper) falls short of the true peak voltage				$2 \cdot 23\,(R_R/R)^{2/3}$
	$RC\omega = 500$	$RC\omega = 1\,000$	$RC\omega = 2\,000$	$RC\omega = 5\,000$	
	%	%	%	%	%
1 000	2·25	2·21	2·20	2·20	2·23
2 000	1·48	1·41	1·40	1·39	1·40
5 000	0·92	0·80	0·77	0·76	0·76
20 000	0·64	0·40	0·33	0·31	0·31
100 000	0·61	0·31	0·17	0·12	0·10
$\pi/RC\omega$, %	0·63	0·31	0·16	0·06	

An examination of the Table shows that, over the range there covered, the accurately calculated error is substantially equal to the larger of the component errors derived from the last row and column. Thus, in the Appendix to the paper where errors under headings (*a*), (*b*), and (*c*) are considered, it would be more accurate to state that the total error of a diode peak voltmeter is equal to the sum of (*a*) and whichever is the greater of (*b*) and (*c*).

* Bowdler, G. W.: Paper No. 2543 M, April, 1958 (see **105** A, p. 176).

† Ackland, R. G., and Keam, D. W.: 'The Measurement of Peak Kilovoltages in X-Ray Equipment,' *Australian Journal of Applied Science*, 1956, 7, p. 273.

‡ Reference should be made to eqn. (12) of the Ackland and Keam paper, which, incidentally, should read $\Delta V \simeq 50\,[3\pi\,(n-1)R_s/nR_1]^{2/3}$ per cent. (There are also three other minor errors in this paper: all signs in eqn. (6*a*) should be positive; the percentage figures in the footnote on p. 285 should be 0·2 and 0·1 respectively; and on p. 287 the cathode connection to the 6X2/EY51 should be to the common filament-cathode lead.)

621.315.211.4

The Institution of Electrical Engineers
Paper No. 2754 S
Oct. 1958

THE DESIGN AND PERFORMANCE OF THE GAS-FILLED CABLE SYSTEM

By E. P. G. THORNTON and D. H. BOOTH, B.Sc.(Eng.), Associate Members.

(*The paper was first received* 7*th November*, 1957, *and in revised form* 25*th August*, 1958. *It was published in October*, 1958, *and was read before the* North-Western Supply Group 21*st October*, *the* Sheffield Sub-Centre 19*th November*, *the* Supply Section 17*th December*, 1958, *and the* North-Eastern Centre 12*th January*, 1959.)

SUMMARY

The gas-filled cable system has been in commercial operation for 20 years, and since it was first described before The Institution in 1943 it has been modified in many points of detail as a result of very considerable service experience and intensive laboratory investigations.

After a brief note on the construction of the cable, a detailed description is given of the unique pre-impregnation process and the experimental work which has been carried out to study the effects of the dielectric, quality of impregnation, material and constructional variables. A description then follows of the design of accessories, testing of cables and miniature systems and of present-day installation methods.

Operational experience with the system is discussed fully, and the modifications resulting from service incidents are detailed. The paper concludes with indications of possible future trends of development which, it is considered, will lead to further technical and economic improvements.

(1) INTRODUCTION

The gas-filled cable system was first described before The Institution by Beaver and Davey in 1943.[1] Since then, owing to the increasing momentum in the bulk transmission of power at high voltages, the extensive use of 33 kV as a primary distribution voltage and the interest in high-voltage submarine cable power links, over 600 000 yd of the cable have been installed. As a result of this service experience, together with an intensive investigation into the behaviour of the dielectric, many detailed changes have been made, and it is felt that a modern assessment of the design and performance of the system is overdue.

Many of the basic principles, such as the use of a non-draining pre-impregnated paper dielectric and the choice of nitrogen as a pressure medium, have remainded unchanged and such matters are discussed in the original paper.[1] The present assessment is also confined to the use of the system on land, since the specialized submarine application has been described elsewhere.[2]

Table 1 gives brief details of the systems installed in Britain and oversea, respectively. Considerable success has been obtained with this cable design for 33 kV distribution oversea, mainly because of its economic advantages and pneumatic simplicity, which results in a relatively small degree of complexity over the more familiar solid-type system.

It will be noted from this Table that the first 33 and 132 kV systems were commissioned in 1937, the latter comprising a trial installation about a mile long inserted in the C.E.B. overhead line at Wimbledon. This cable was taken out of service in 1951, since the conductor size was limiting the system capacity, and its examination is described in Section 8.5.

The system has been proved experimentally up to 275 kV, and the first commercial installation in this country at this voltage is due to be made at the end of 1958.

(2) CONSTRUCTION AND DESIGN

The cable constructions at present in use for single-core and 3-core gas-filled cables are shown in Figs. 1(*a*) and (*b*), respectively. Pre-impregnated paper strips, graded in thickness, are lapped in air on to a conventionally stranded but screened conductor, the individual cores being screened with copper tape or metallized paper.

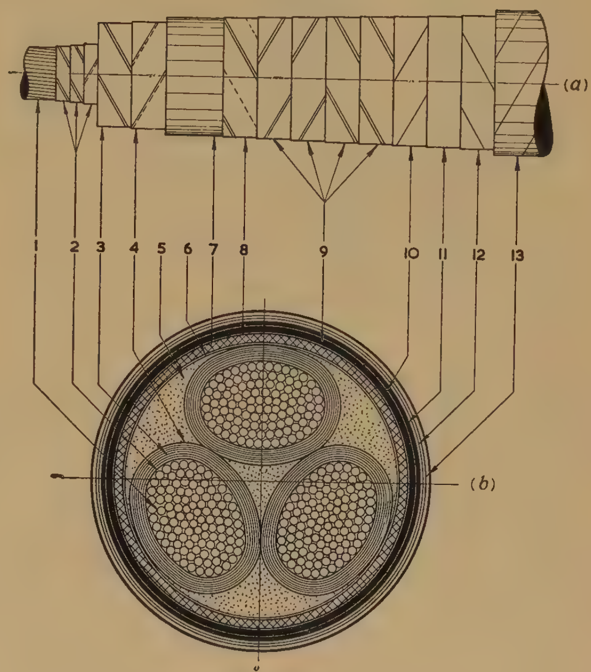


Fig. 1.—Typical gas-filled cables.

1. Conductor.
2. Conductor screen.
3. Dielectric.
4. Dielectric screen.
5. Jute fillers.
6. C.W.F.T. binder.
7. Lead sheath.
8. Copper-wire-woven fabric tape.
9. Reinforcing tapes.
10. Bituminized cotton tape.
11. Rubber sheath.
12. Carbon-impregnated tape.
13. Hessian tapes.

(*a*) Single-core, 132 kV.
(*b*) 3-core, 33 kV.

For 3-core construction the cores are laid up using pre-impregnated jute strings in the interstices and are sheathed with a lead alloy. For single-core cables having a conventional stranded conductor, an annular clearance space is left under the lead sheath to act as a primary gas-charging channel. This gas annulus is not required on the rare occasions when hollow conductors are used. Sheathing is carried out using a vertical lead-press[3] fitted with a tray to provide vacuum filling, and the sheath is then reinforced with metallic tapes. These tapes are protected against corrosion by a sheath of vulcanized rubber,[4] which is followed by conventional bitumen-compounded textile servings for mechanical protection. It is unusual for land cables to be armoured, since the site testing of the anti-corrosion covering and the supervisory nature of the internal gas pressure

Mr. Thornton and Mr. Booth are with W. T. Glover and Co., Ltd.

Table 1A

Installations in Great Britain

Commissioning date	Location	Voltage	Number of cores	Conductor section	Cable length
		kV		in²	yd
1937	Hinkley–Sapcote	33	3	0·10	4 000
1937	Wimbledon	132	1	0·30	5 280
1939	Robin Hood–Mill Close	33	3	0·10	14 000
1940	Sheffield	33	3	0·40	5 600
1940	Sheffield	33	3	0·40	7 000
1940	Sheffield	33	3	0·40	4 000
1940	Brimsdown	132	1	0·25	2 400
1940	Woking	132	1	0·30	1 230
1942	Little Barford	132	1	0·30	2 260
1942	Liverpool–Birkenhead	132	1	0·40	31 000
				0·60	
1943	Sheffield	33	3	0·40	3 700
1943	Sheffield	33	3	0·40	3 700
1943	Colchester–Coggeshall	66	3	0·15	5 480
1944	Oxford–Gloucester	132	1	0·40	6 000
1947	Bedford	132	1	0·30	1 200
1950	Hartshead	132	1	0·30	780
1950	Sheffield	33	3	0·40	
				0·60	12 000
1950	Sheffield	33	3	0·40	1 600
1951	Sheffield	33	3	0·30	3 180
1951	Sheffield	33	3	0·40	2 000
1951	Capenhurst	132	1	0·30	300
1952	Chadderton	132	1	0·30	320
1952	Blackburn	132	1	0·25	530
1953	Brimsdown	132	1	0·30	2 130
1953	Deptford East	66	1	0·60	4 200
1954	Woolwich–Eltham	33	1	1·00	3 670
1954	Carlisle	132	1	0·50	300
1954	Carrington	132	1	0·50	1 500
1954	Woolwich–Eltham	132	1	0·30	34 800
				0·35	
1955	Carrington	132	1	1·00	
				0·60	6 270
				0·50	
1955	Windscale	132	1	0·35	610
				0·60	
1955	Sheffield	33	3	0·40	9 290
				0·60	
1956	Iver	132	1	0·50	1 560
1956	Penwortham	132	1	0·50	2 120
1956	Capenhurst	132	1	0·20	9 540
				0·45	
1956	Brunswick Wharf–Finsbury Market	132	1	0·60	81 000
				0·75	
1956	Hams Hall	132	1	0·20	21 420
				0·30	
				0·75	
1956	Uxbridge–North Hyde	66	3	0·50	19 950
				0·75	
1957	Manchester	33	3	0·40 Al	3 920
1957	Manchester	33	3	0·30 Al	8 000
1957	Sheffield	33	3	0·45	5 750
				0·40	
				0·30	
				0·25	
1957	Plymouth	33	3	0·5 Al	8 200
1957	London Backhill–Whitfield Street	33	3	0·5 Al	9 290
				0·3	
1957	Manchester	33	3	0·35 Al	2 800
1957	Stocksbridge	66	3	0·15	1 100
1957	Finsbury Market–Holborn	132	1	0·75	31 230
				0·60	
1957	Kings Lynn	132	1	0·4	3 255
1957	Camarthen Bay	132	1	0·35	230
1957	Little Barford	132	1	0·45	1 190
				0·20	
1957	Chadderton	132	1	0·35	2 600
1957	Hams Hall	132	1	0·40	450
1957	Bourne	132	1	0·35	270
1957	Windscale	132	1	0·45	360

Table 1B

OVERSEA INSTALLATIONS

Commissioning date	Location	Voltage	Number of cores	Conductor section	Cable length
		kV		in²	yd
1941	*Detroit Edison, U.S.A.	120	3	0·47	11 800
1942	Sydney, Australia	33	3	0·15	100
1948	*Detroit Edison, U.S.A.	138	3	1·18	12 430
1955	Capetown, South Africa	66	3	0·50 0·65	23 200
1955	Capetown, South Africa	33	3	0·15	16 000
1956	Durban, South Africa	33	3	0·20	2 420
1956	Salisbury, Rhodesia	33	3	0·30	18 640
1956	New South Wales Railway, Australia ..	66	1	0·20	1 170
1956	†Vancouver, British Columbia	138	1	0·35	162 500
1957	Calcutta, India	33	3	0·35 Al	4 500
	Calcutta, India	33	3	0·35 Al	
1957	Pretoria, South Africa	33	3	0·35 Al 0·275 Al	7 140
1957	Capetown, South Africa	33	3	0·30	3 290
1957	Waratah, Australia	33	3	0·45 Al	5 330
1957	Pyrmont, Australia	33	3	0·55 Al	13 800
1957	Capetown, South Africa	66	3	0·50	350

* Pipe-line cables manufactured in the United States.
† Submarine cable.

provides both immediate and long-term indication of damage to the cable. The cable is not subjected to full nitrogen pressure until after laying and jointing, when, after a gas-tightness test, the gas pressure is adjusted to the normal operating level of 200 lb/in².

To date, 3-core cables have been manufactured commercially only for 33 and 66 kV, but it is only plant limitations that have hitherto prevented this construction from being used at 132 kV.

The salient features of the construction and design are given in Section 13.

(3) PRE-IMPREGNATION PROCESS

The performance of the gas-filled cable dielectric is based on the unique pre-impregnation process, and it is therefore essential that this should be described in detail. A typical machine used for pre-impregnation is shown in Fig. 2. This illustrates the modern practice of twin impregnation, although the majority of cables so far installed have been manufactured on a single-paper machine illustrated in the original paper.[1]

The paper rolls, as received from the supplier, are mounted behind the machine, and the paper is fed over two electrically-heated thermostatically-controlled drying rollers. These rollers operate at 200° C and reduce the moisture content of the raw paper from about 8% to less than 0·1%. The papers are then fed through a sealing gland into a chamber evacuated to approximately 20 mm Hg. The dried and degasified paper is passed through a second vacuum seal directly into the molten impregnant, the surface of which is at atmospheric pressure, so that

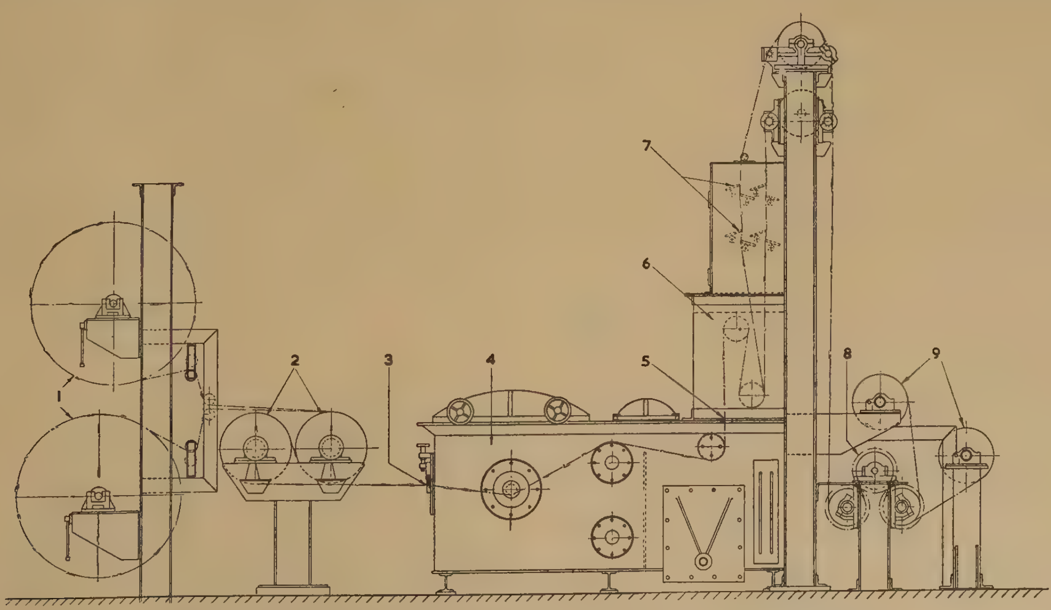


Fig. 2.—Vacuum-drying and impregnating machine for twin impregnation.

1. Rolls of raw paper.
2. Electrically-heated thermostatically-controlled drying rollers.
3. First vacuum sealing gland.
4. Vacuum chamber.
5. Second vacuum sealing gland.
6. Impregnating tank.
7. Heated scraper knives.
8. Driving rollers.
9. Take-up mandrels for impregnated paper.

impregnation takes place at a positive pressure of 15 lb/in^2 absolute. At this stage the two papers are separated, passed through scraper knives steam heated to 90° C, and are then taken up on separate mandrels at the rear of the machine.

The non-draining nature of the dielectric is obtained by the control of surface compound by means of the scraping process and not by the use of a high-melting-point impregnant. In fact, the physical nature of the impregnant is decided on its low-temperature characteristics as applied to ultimate bending performance.

The machine is fully equipped with recording instruments and the whole process lends itself to critical quality control, so that the quality of the dielectric is assured before it is applied to the cable.

After impregnation, the rolls of paper may be stored for considerable periods without deterioration, but as a precaution against possible contamination, the outer turns and end-cuts of the rolls are rejected before the paper is slit to width, which is done immediately before it is applied to the cable. The lapping is carried out in the normal factory atmosphere on machines designed to give tangential application of each paper under controlled-tension conditions.

Since there are no subsequent drying and impregnating processes, the paper suffers no dimensional changes and the tensions applied at the lapping machine are maintained. This factor, together with the low frictional coefficient of pre-impregnated paper, is of considerable assistance in obtaining a high dielectric quality and a good bending performance.

The process of pre-impregnation removes the normal limitation due to the finite capacity of the impregnation tanks and therefore facilitates the manufacture of long cable lengths.

(4) PRE-IMPREGNATED DIELECTRIC: EFFECT OF IMPREGNATION MATERIAL AND CONSTRUCTIONAL VARIABLES

(4.1) General

The performance of the dielectric has been studied using cable-model techniques,[5,6] and the value of this type of work in modern high-voltage-cable development cannot be too highly stressed.

(4.2) Impregnation Variables

The operating conditions of the pre-impregnation machine have been determined by consideration of the results from many tests with varying speeds, drying-roller temperatures and vacua. The optimum values of impulse strength, power factor and mechanical characteristics are required, and, as shown in Section 4.5, the moisture content of the impregnated paper roll should be below 0·2% in order to obtain a satisfactory moisture content in the completed cable.

To illustrate the type of data obtained from such investigations, Table 2 gives results of tests carried out on a single-paper machine impregnating 4-mil wood-pulp paper with an air impermeability of approximately 2000 sec per 100 cm^3 and a density of 0·8 g/cm^3. In all cases measurements were made of compound content, moisture content, air content, tensile strength, elongation, impulse strength and power factor at 80° C. A range of speeds from 27 to 71 ft/min was used, and the roller temperature and vacuum were maintained at the normal operating levels of 200° C and 20 mm Hg.

As would be expected, the characteristic most affected by increase of speed is the moisture content, although it is interesting to note that this increase is reflected only in the power factor at 80° C, which starts to increase with machine speeds over 50 ft/min.

When considering roller temperature, both the continuous running and the stationary condition must be taken into account.

Table 2

EFFECT OF IMPREGNATING MACHINE SPEED ON PRE-IMPREGNATED PAPER CHARACTERISTICS

Machine speed	Moisture content	Power factor at 80° C
ft/min	%	
27	0·06	0·0024
35	0·15	0·0025
51	0·39	0·0025
60	0·57	0·0028
65	0·60	0·0032
67	0·63	0·0034
71	0·72	0·0042

Roller temperature = 200° C.
Vacuum = 20 mm Hg.

The moisture content decreases with increase of temperature and is approximately 0·1% at 200° C. At this temperature and with a machine speed of 35 ft/min the paper is not in any way damaged, and, in fact, stoppages of up to 1 min can be tolerated. In the event of longer delays the paper in contact with the drying rollers is rejected.

To study the effect of the degree of vacuum, a range from 10 to 760 mm Hg was covered. The moisture content is unaffected over this range, showing that all moisture removal occurs at the heated rollers. The important characteristics are now air content and impulse strength, and it can be seen from Fig. 3 that impulse equilibrium is reached at 40 mm Hg.

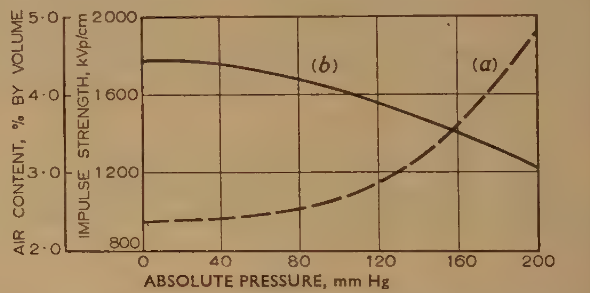


Fig. 3.—Variation of air content and impulse strength with pressure.

Machine speed = 35 ft/min.
Roller temperature = 200° C.
(a) ---- Air content.
(b) —— Impulse strength.

As a result of these tests, standard conditions of 35 ft/min maximum machine speed, 200° C roller temperature and 20 mm Hg vacuum were adopted for this type of paper. In a similar manner, conditions have been laid down for other types of paper.

(4.3) Material Variables

(4.3.1) Paper.

The importance of the physical characteristics of paper and their relation to the electrical performance of high-voltage-cable dielectrics has recently become subject to controversy.[5–7] The common objective has been the improvement of cable impulse-breakdown strength by choosing the optimum combination of the basic paper characteristics of air impermeability and density. Breakdown tests carried out on sheet-paper and cable models have indicated the primary importance of the density of the paper used for the gas-filled dielectric. For 4-mil wood-pulp paper the following empirical relationship has been established for cable design purposes:

$$x = 67y + 1075z + 530$$

where x = Impulse strength, kV(peak)/cm.
$y = \log_{10}$ (impermeability), impermeability being measured in seconds per 100 cm^3.
z = density, g/cm^3.

Thus, paper having an impermeability of 3 000 sec and a density of 0·78, and of the same type as that used in this experiment, would have an impulse strength of 1 600 kVp/cm (kV peak) and the relative effects of impermeability and density would be 14·7 and 52·3%, leaving a residual of 33·0%.

This latter is probably accounted for mainly by variation in paper uniformity as indicated by Hall and Kelk,[8] and this aspect offers one very attractive avenue for overall improvement of paper quality.

It can be seen from the form of the above equation that the effect of impermeability is very important at low levels, but very little effect is found above 1 000 sec. For example, a change from 1 000 to 3 000 sec results in only a 2% improvement in impulse breakdown strength, and this could have been obtained by a 4% change in density.

(4.3.2) Impregnant.

Since the advent of the gas-filled cable, no significant change in the impregnant has been made. The standardization of impulse voltage testing at 85° C in Great Britain has focused attention on the effect of conductor temperature on impulse strength and the role played by the impregnant. Table 3 shows

Table 3

EFFECT OF TEMPERATURE ON IMPULSE STRENGTH

Temperature °C	Number of tests	Mean impulse strength
deg C		kVp/cm
20	6	1 130
85	8	830

65/35 Registration; conductor diameter = 1 in; gas pressure = 200 lb/in^2.

typical results obtained using 4-mil pre-impregnated paper of 2 580 sec impermeability and 0·8 density, lapped on to a steel mandrel and tested under 200 lb/in^2 gas pressure. The decrease of impulse strength with temperature is most marked, and this is thought to be due to the very low viscosity of the impregnant at 85° C.

Research is now in progress to determine whether the blending of the present type of paraffinic jelly with suitable additives will improve the impulse strength at high temperatures by virtue of the increase of impregnant viscosity.

(4.4) Constructional Variables

(4.4.1) General.

A detailed study of the effect of the constructional variables on impulse and a.c. performance has been made using cable-model and flat-electrode techniques. For all tests the impermeability of the papers was in the range 3 000–7 000 sec, and the density between 0·8 and 0·9.

For the a.c. characteristics the ionization inception voltage, measured using a discharge detector,[9] was used as the criterion, since with a dielectric with a non-migratory impregnant and gas-filled butt gaps the onset of ionization will determine the ultimate a.c. performance of the dielectric.

(4.4.2) Conductor Diameter.

The impulse tests were carried out at atmospheric pressure with $\frac{5}{16}$ and $\frac{5}{8}$ in conductor-diameter models, and at 200 lb/in^2 gas pressure using $\frac{1}{2}$ and 1 in diameters. The gas-pressure conditions were similar for the a.c. tests, but the conductor diameters were $\frac{5}{16}$ and $\frac{3}{4}$ in. All results are shown in Table 4.

Table 4

EFFECT OF CONDUCTOR DIAMETER ON IMPULSE STRENGTH AND IONIZATION INCEPTION STRESS

Conductor diameter	Thickness	Gas pressure	Number of tests	Mean impulse strength	Ionization inception stress
in	mils	lb/in^2		kVp/cm	kV/cm
$\frac{5}{16}$	$2\frac{1}{2}$	Atm	8	810	—
$\frac{5}{8}$	$2\frac{1}{2}$	Atm	8	815	—
$\frac{5}{16}$	$1\frac{3}{4}$	Atm	5	—	39
$\frac{3}{4}$	$1\frac{3}{4}$	Atm	5	—	37
$\frac{1}{2}$	4	200	12	1 245	—
1	4	200	13	1 150	—
$\frac{5}{16}$	$1\frac{3}{4}$	200	5	—	187
$\frac{3}{4}$	$1\frac{3}{4}$	200	5	—	190

65/35 Registration; 20° C.

Under impulse conditions there is no diameter effect at atmospheric pressure, but at 200 lb/in^2 the use of the 1 in-diameter conductor lowers the impulse strength by 8%. Under a.c. conditions there is no significant conductor-diameter effect at either atmospheric or full gas pressure.

(4.4.3) Conductor Screening.

The possible effect of conductor screening has so far been examined only under impulse conditions, but the effect on a.c. characteristics is under investigation. The impulse tests were carried out using inner electrodes $\frac{3}{4}$ in in diameter, one being smooth and one stranded with 27 wires of 80 mils diameter in the outer layer. In both cases the dielectric thickness was approximately 65 mils. On the basis of the work of Levi-Cevita[10] the theoretical increase in maximum stress introduced by stranding would be approximately 20%. The tests were carried out at an internal gas pressure of 200 lb/in^2 and the results are given in Table 5.

Table 5

EFFECT OF STRANDING ON IMPULSE STRENGTH

Type of conductor	Thickness	Number of tests	Mean impulse strength
	mils		kVp/cm
Smooth . .	4	5	1 245
Stranded . .	4	4	1 115

65/35 registration, 20° C and 200 lb/in^2.

It will be seen that there is a significant stranding effect of 10%, which, although not as high as the theoretical, is in general agreement with the work of Howard and Browning.[11]

(4.4.4) Paper Thickness.

$1\frac{3}{4}$, $2\frac{1}{2}$ and 4-mil thickness papers were used for the impulse breakdown tests. The papers in the form of 1 in-wide tapes were applied to smooth brass inner electrodes $\frac{3}{8}$ in in diameter. The tapes were lapped with a load of $1\frac{1}{2}$ lb weight, a $\frac{1}{16}$ in butt gap and a nominal registration of 65/35. In order that, for each model, all possible breakdown paths through the dielectric should contain the same proportion of paper tapes to gaps,

the total number of layers of paper in each case was made a multiple of three. In order to satisfy this condition and to keep the total wall thickness for all three papers approximately constant, 21 layers of 1¾-mil paper, 15 layers of 2½-mil paper or 9 layers of 4-mil paper were used. For the a.c. investigation, 1¾- and 4-mil papers were used, applied to ¾ in-diameter electrodes. The impulse and a.c. results are shown in Table 6. All tests were carried out at 200 lb/in^2.

Table 6

EFFECT OF PAPER THICKNESS ON IMPULSE STRENGTH AND IONIZATION INCEPTION STRESS

Thickness	Number of tests		Mean impulse strength	Ionization inception stress
	Impulse	A.C.		
mils			kVp/cm	kV/cm
1¾	7	5	1 180	190
2½	8	–	1 170	—
4	10	5	1 130	157

65/35 registration, 20° C and 200 lb/in^2.
Conductor diameters = ⅝ in (impulse) and ¾ in (a.c.).

With the gas-filled dielectric it is clear that the paper thickness does not significantly affect impulse performance, and this is the reverse of the results obtained for the oil-filled dielectric.[6] Under a.c. conditions, however, there is a 21% increase in ionization stress when 1¾-mil papers are used in place of 4-mil papers, and it is for this reason that a dielectric graded by thickness has been incorporated in gas-filled cables.

(4.4.5) Paper Registration.

The effect of paper registration has been examined only under impulse conditions, using 2½-mil paper lapped with nominal registrations of 50/50, 65/35, 75/25 and the results are shown in Fig. 4. Parallel tests were also carried out using a flat-plate

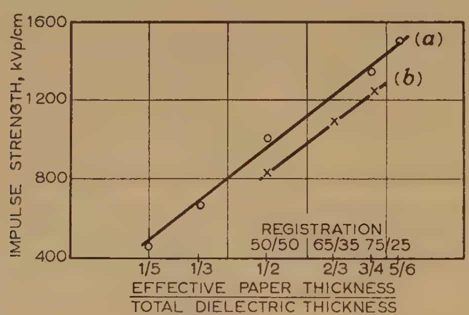


Fig. 4.—Variation of impulse strength with registration.
2·5-mil paper.
Gas pressure = 200 lb/in^2 gauge.
Temperature = 20° C.
(a) Test cell.
(b) Cable models.

electrode system and the results obtained are also given in this Figure. It will be seen that there is a most significant improvement of impulse strength with increase in the ratio between effective paper thickness and total dielectric thickness.

For practical application the inherent wander of paper registration prevents consistent use being made of registrations of the order of 75/25, and 65/35 is the preferred figure. It is difficult to assess the effect on impulse strength of the random distribution of registration, but one would expect it to be generally advantageous.

(4.4.6) Gas Pressure.

When investigating the effects of gas pressure on impulse strength both cable models and flat electrodes have been used, and the results are shown in Fig. 5. For the a.c. investigation, only models have been studied, with the results as shown in Fig. 6.

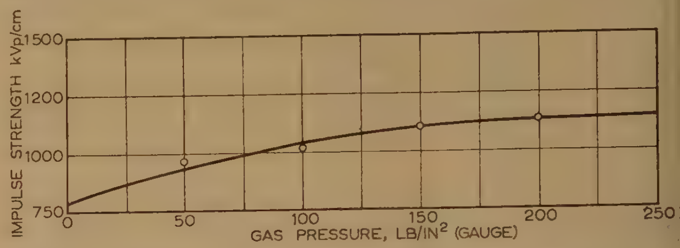


Fig. 5.—Variation of impulse strength with applied gas pressure.
1¾-mil paper.
Registration = 65/35.
Temperature = 20° C.

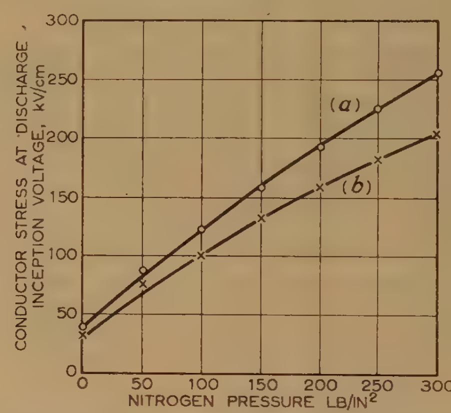


Fig. 6.—Variation of discharge inception stress with nitrogen pressure at ambient temperature.
(a) 1¾-mil paper.
(b) 4-mil paper.

The impulse strength and the ionization inception stress both increase with increase in applied gas pressure. At 200 lb/in^2, however, further increase in gas pressure to 250 lb/in^2 would provide only a small improvement in impulse strength, but would give an 18% improvement in ionization stress with 1¾-mil paper.

(4.5) Moisture Content of Cable Dielectric

(4.5.1) Rolls of Impregnated Paper.

As mentioned in Section 5.2.1, the rolls of impregnated paper may be stored for comparatively long periods after processing. Table 7 shows typical moisture contents obtained directly after impregnation and after storage in the factory atmosphere.

Table 7

EFFECT OF STORAGE TIME ON MOISTURE CONTENT OF IMPREGNATED PAPER ROLLS

Paper thickness	Storage time	Moisture content	
		Immediately after impregnation	After storage
mils	months	%	%
1¾	22	0·16	0·23
2½	20	0·18	0·26
4	3	0·10	0·16

The above results, taken under exaggerated conditions, show that roll storage under normal factory conditions is quite satisfactory. Detailed investigation has shown that rolls with this order of moisture content will produce completed cables having moisture contents in accordance with the values stated in the following Section.

(4.5.2) Completed Cables.

As part of the normal quality-control procedure, regular measurements are made of the moisture content of completed cables. All measurements are made using the Karl Fischer technique and the samples are taken from the cable ends, which will naturally tend to give the worst result to be expected on any given length.

Measurements have been made on many hundreds of completed cables, and the overall mean moisture content has been found to be 0·38% with a standard deviation of 0·13. It is estimated that at least half of this total variance is due to sampling and experimental errors.

The service record of the gas-filled cable is sufficient proof of the validity of operating at moisture contents of this order. Before the institution of the rigid quality control which has been imposed in recent years, it is probable that many of the earlier cables installed had moisture contents higher than those quoted above.

(4.5.3) Experimental Evidence.

While service experience is the main criterion of long-term a.c. performance, an investigation has been made on sheet-paper samples and cable models into the effect of moisture on the shorter-term electrical characteristics. Impulse breakdown is unaffected up to moisture contents of 0·8%, and even then the rate of fall-off is small. The power factor at ambient temperature increases from 0·0030 at 0·3% to 0·0035 at 1·0% but a steep rise in power factor does not occur until a moisture content of 3% is reached. At 80° C, however, the power factor increases appreciably with moisture contents above 0·6%. Step-breakdown a.c. tests show a declining strength at 0·8% and the voltage/time-to-breakdown characteristic remains unchanged up to at least 0·6% moisture content.

(4.5.4) Summary of Evidence.

The experimental results confirm that gas-filled cables manufactured with moisture contents within the range given in Section 4.5.2 will have an adequate margin of safety with respect to all the important electrical characteristics.

(5) ACCESSORIES

(5.1) Electrical Design

The electrical design of accessories for the gas-filled cable follows a pattern very similar to that quoted by Brazier.[12]

In joints, the conductors are joined by a sweated ferrule of semi-flush design, and on each side the cable dielectric is tapered by the continuous-wire method to produce an average slope of 40 mils/in. The joint dielectric is built up from hand-applied pre-impregnated paper tapes, a small amount of varnished Terylene tape being used at the interface between the hand-applied paper and the tapered cable dielectric. The overall diameter of the joint insulation is adjusted so that the stress at the ferrule surface does not exceed 65% of the conductor stress of the cable. The transition between the diameter over the cable dielectric and that of the joints is made with a smooth taper, the design of which is based on a maximum longitudinal stress of 3 kV/cm. The whole joint dielectric is fully screened using conducting tape and tin-foil.

In sealing ends, stress cones built up with hand-applied Terylene tape are used for all except 132 kV 100 kV/cm cable designs. The slope of the stress-cone profile is such as to limit the longitudinal stress to 2 kV/cm, and the diameter of the cone is fixed so that the radial stress at the termination of the lead wire is limited to 10 kV/cm. For 132 kV 100 kV/cm cables, because of the high screen stresses, preformed paper-roll stress cones are used in conjunction with a stress-control ring.[13] For voltages above 132 kV, stress control has been provided by means of a hand-made condenser cone.

All designs using Terylene-taped stress cones utilize a bituminous filling compound within the porcelain, but for the paper-roll and condenser-cone designs, oil/polyisobutylene filling is used.

(5.2) Mechanical and Pneumatic Design

(5.2.1) Straight-Through Joints.

The modern 3-core straight-through joint shown in Fig. 7 comprises a flanged pressure-retaining sleeve made gas tight by means of O-ring seals. These O-rings are used to provide both flange- and barrel-type seals. The longitudinal component of stress within each layer of the reinforcement is transferred to the joint sleeve by means of a small cast plumb at each end of the joint. The O-ring seals are arranged so that, after the cast plumbs are made and the electrical part of the joint is completed, the sleeve may be drawn over the completed joint and the whole assembly made gas-tight by bolting together the two flanges. No filling compound is used, and this form of joint has the advantage that once the cast plumbs are made the sleeve may be drawn over the joint as a complete protection, should the joint hole be in danger of flooding or if it is decided for any reason to suspend jointing for a period.

The joint sleeve is fitted with copper pipes brazed into the end flange of the joint. One pipe passes directly into the sleeve and the other pipe is made off into the neoprene or p.v.c. breeches piece which forms a small pneumatic restriction at one

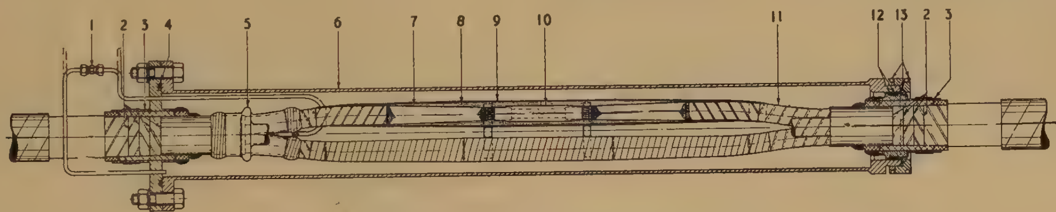


Fig. 7.—Typical 3-core-cable straight-through joint.

1. Mechanical union between gas pipes.
2. Reinforcing tape termin ·ions.
3. Cast plumb container.
4. O-ring (flange application).
5. Neoprene or p.v.c. breeches-piece.
6. Steel sleeve.
7. Tapered cable insulation.
8. Hand-applied insulation.
9. Overall screening.
10. Semi-flush jointing ferrule.
11. Screened cable core.
12. O-rings (barrel application).
13. Locking and centralizing rings.

end of the joint. Both pipes, suitably protected, may be carried through the ground to gas stop-valves mounted in the surface boxes in the roadway or pavement. These valves may be used to assist in the rapid pressurizing of the completed installation, and under gas-leak conditions they facilitate the location of the leak by the measurement of the gas pressure and the rate and direction of flow of the gas. Joints fitted with pipes terminating in a surface valve-box are called 'intermediate charging joints' and are provided every 1 000–2 000 yd. Where not required, the two gas-entry pipes from the joint sleeve are joined together within the concrete box surrounding the joint.

The single-core joint embodies similar principles and is shown in Fig. 8. It should be noted that for single-core joints copper sleeves are used, but for 3-core joints steel sleeves are satisfactory and more economical.

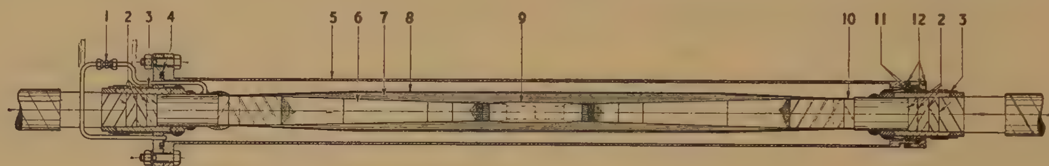


Fig. 8.—Typical single-core straight-through joint.

1. Mechanical union between gas pipes.
2. Reinforcing tape terminations.
3. Cast plumb container.
4. O-ring (flange application).
5. Copper sleeve.
6. Tapered cable insulation.
7. Hand-applied insulation.
8. Overall screening.
9. Semi-flush jointing ferrule.
10. Screened cable core.
11. O-rings (barrel application).
12. Locking and centralizing rings.

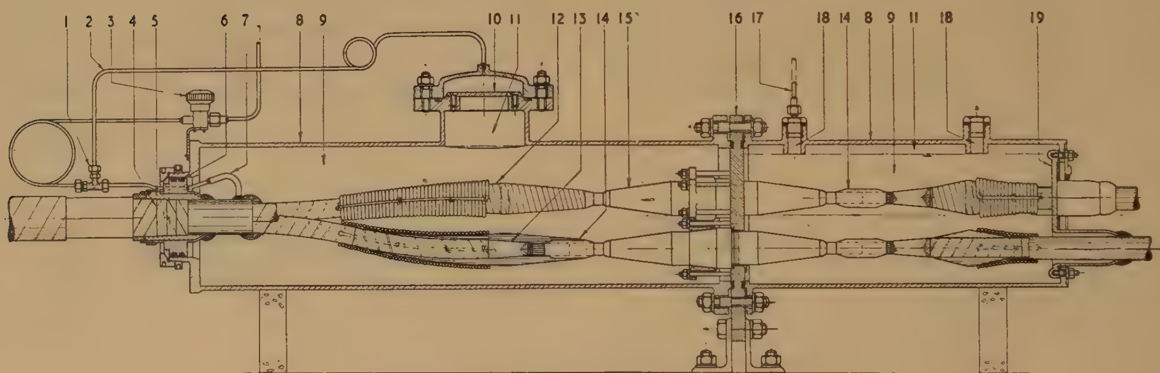


Fig. 9.—Typical 3-core terminating joint.

1. Mechanical gas-pipe connector.
2. Pressure-equalizing pipe.
3. Stop valve.
4. Reinforcing tape terminations.
5. Cast plumb container.
6. O-ring seals (barrel application).
7. Cable gas-feed pipe.
8. Steel sleeve.
9. Compound filling.
10. Baffle plate.
11. Compound expansion space.
12. Hand-applied stress cone.
13. Tapered cable insulation.
14. Soldered cable connection.
15. Bakelized condenser bushing.
16. Barrier plate.
17. Pipe to pressure indicator or relief valve.
18. Filling holes.
19. Solid cable gland plate.

(5.2.2) Terminating Joints.

For 33 kV working it is customary to terminate gas-filled cables with conventional single-core solid-type tails, because in many cases the switchgear or transformer has not been designed to accommodate oil-immersed pressure-type sealing ends. The joint for this purpose is known as a 'terminating joint' and a typical arrangement is shown in Fig. 9.

This joint involves the use of a pressure-tight casting or prefabricated sleeve fitted with a barrier plate through which the three conductors are passed by means of Bakelized condenser bushings manufactured on solid copper stalks. The conductors of both solid and gas-filled cable are sweated to the copper stalks by means of ferrules, and stress cones are used on both cable ends. Both halves of the joint are filled with bitumen compound to prevent internal flashover. These joints are usually arranged so that the nitrogen can be fed into the gas-filled half from the gas-charging cubicles.

Similar designs of terminating joint have also been produced for use at 66 kV for the rare occasions when connection has to be made to 66 kV solid-type cables.

It is sometimes convenient to terminate the 3-core gas-filled cable direct into pressure-type sealing ends. This may be carried out by using trifurcating joints or splitter boxes and reinforced lead-alloy pipes.

(5.2.3) Gas Sectionalizing Joint.

On installations more than 5 miles long it may be convenient to sectionalize the pneumatic system completely, in order to reduce the time of recharging the cable with gas should a leak occur and a repair be necessary.

(5.2.4) Sealing Ends.

Sealing ends, as shown in Fig. 10, are of the single-pressure porcelain type and make use of the flange application of the O-ring seal. Provision is normally made at the sealing end for the introduction of the gas into the cable after laying and jointing. Gas is admitted through an insulated gas-feed pipe and externally mounted stop-valve into a gas-feed gland, the bottom end of which is plumbed over the open end of the lead sheath. Entry of sealing-end filling compound into this gland is prevented by provision of a taped poultice over the tapered

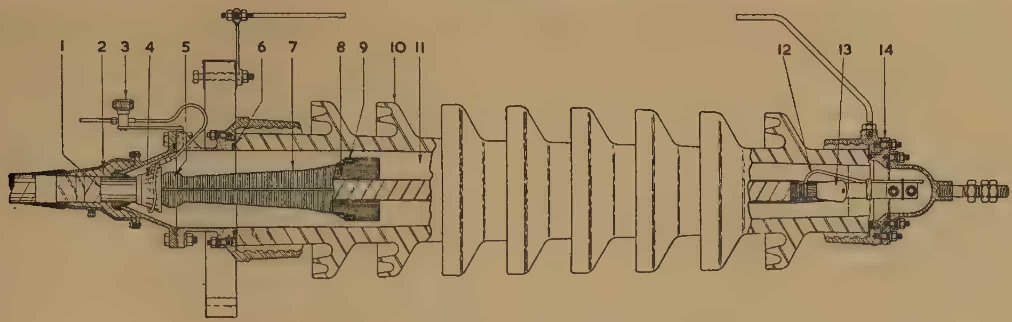


Fig. 10.—132 kV 100 kV/cm outdoor-type sealing end.

1. Reinforcing tape termination.
2. Cast plumb container.
3. Stop valve.
4. Gas-feed gland.
5. Taped poultice.
6. O-ring (flange application).
7. Lead wire.
8. Preformed paper-roll stress cone.
9. Stress-control ring.
10. Pressure porcelain insulator.
11. Compound filling.
12. Gas-equalization pipe.
13. Soldered cable connector.
14. Connector ring bolted to cable connector.

top extension to the gland. Sealing-end filling compounds absorb gas into solution and, on degassing the cable system, the gas pressure within the sealing end falls more slowly than within the cable. The presence of this pressure differential during degassing makes it necessary for the gas-feed gland to be sufficiently rigid to prevent collapse.

(5.2.5) **Aluminium Jointing.**

In recent years, on economic grounds, use has been made of aluminium conductors for gas-filled cables. The jointing and terminating of these cables has been entirely conventional, except that special organic fluxes and zinc-bearing solders have been used. The original solders contained cadmium, but cadmium-free solders have recently been developed because of the possible dangers of cadmium poisoning.

(5.3) Gas-Charging Equipment

In its simplest form gas-charging equipment, housed in a suitable cubicle, consists of pressure gauges connected to the cables to indicate the internal gas pressure, together with a battery of two or three cylinders of nitrogen connected to the cable feed pipes through stop valves and a 2-stage pressure-controlled regulator. A further pressure gauge is usually fitted to the cylinder manifold to indicate the pressure of gas within the cylinders themselves. The pressure-controlled regulator allows the passage of gas into the cable only if the cable pressure drops owing to a gas leak. The various gauges are fitted with electrical contacts which may be connected to audible and visible warning signals in the control room or substation. The sequence of these signals is such that the first warning comes from the pressure gauge on the cylinders, indicating that a gas leak is occurring and gas is being fed into the cable. The second comes from one of the cable pressure gauges, indicating that gas pressure in the cable has fallen to 180 lb/in^2. The cable may safely be kept in operation so long as the gas pressure, as indicated by the gauges in the charging equipment, is kept above the minimum value of 125 lb/in^2. A case has occurred where a cable was left in service for 12 weeks even though external mechanical damage had caused a leak of sufficient magnitude to require the replacement of nitrogen cylinders every 24 hours in order to maintain the minimum pressure. After a local repair the cable was recommissioned and is still in service.

(6) TESTING

(6.1) Factory Routine

All finished cables are subjected to a 30 lb/in^2 internal gas pressure test to ensure the integrity of the lead-alloy sheath. The normal routine tests of conductor resistance, insulation resistance and capacitance are then carried out.

The cable dielectric is, of course, not complete until it is fully pressurized, but this is not done in the factory, since the resulting distension would tend to lock the reinforcing tapes and restrict the flexibility of the cable during laying. For this reason the routine power-factor/voltage test is carried out only up to half working voltage at atmospheric pressure and a d.c. high-voltage test is used rather than the more usual a.c. test.

In order to ensure the soundness of the rubber sheath before despatch, a direct voltage of 12 kV d.c. is applied between the reinforcement and the carbon tape over the rubber layer, immediately before the cable leaves the factory.

(6.2) Type and Design

The principle of type-approval testing for the C.E.G.B. is now so well known that there is little point in detailing the form of these tests, although their value in testing complete miniature systems must be emphasized. It is sufficient to say that, with the modern designs of cables and accessories, as detailed in the previous Sections, the C.E.G.B. requirements are met completely and with an adequate margin.

The principle of withstand testing provides an adequate criterion for the customer in ensuring a satisfactory level of performance. For the manufacturer's information only, it is desirable on both technical and economic grounds that these tests should be extended to determine the ultimate levels of performance, in order to provide design data as a basis for future development. The two most important of the type tests are the impulse-voltage test and loading-cycle test, with its specified extension at 132 kV to a test of thermal stability. These may be conveniently extended to impulse breakdown and to breakdown under thermal instability, respectively. It should be noted that hitherto the stress at the impulse withstand voltage has controlled the a.c. operating stresses quoted in Section 13.2.

A 132 kV 100 kV/cm 0·2 in^2 single-core gas-filled cable system was tested successfully at the withstand level of 640 kVp at 85° C, and when the voltage was increased in steps of 20 kVp, with ten impulses of each polarity at each voltage level, breakdown finally occurred in the straight-through joint at 720 kVp, which is equivalent to a cable conductor stress of 940 kVp/cm.

A second system using similar cable, after successfully completing the loading cycle and thermal stability tests, was taken to thermal instability by increasing the loading current in steps. Again breakdown occurred in the straight-through joint with a cable-conductor temperature of 140° C. Subsequent to these

tests, radial power-factor examination of the cable dielectric showed no sign of degradation.

(6.3) After Installation

Immediately after the laying and slabbing over of each length, the anti-corrosion covering is tested at 10 kV d.c. A voltage of this order was selected on the basis of that necessary to detect the self-sealing type of fault which can occur with knife cuts or punctures due to sharp stones. The insulation resistance of the serving is also checked.

When jointing has been completed the system is subjected to a gas-pressure test at the maximum operating pressure of 250 lb/in^2.

The system is finally tested electrically by the application of a d.c. voltage test at twice the voltage between phases.

(7) INSTALLATION AND GAS CHARGING

(7.1) Laying

Gas-filled cables may be laid in all the standard conditions of installation, but, since they are generally unarmoured, certain extra precautions should be taken during their laying to minimize the risk of mechanical damage. Cables may be pulled with loads up to 10 000 lb/in^2 of copper conductor and 7 500 lb/in^2 of aluminium conductor, provided that the cable end is fitted with a pulling eye in which the conductors, lead-alloy sheath and reinforcement are all locked together. Experience has shown that very long lengths, up to a 1 000 yd, may be installed in this manner using a motorized winch.

Reference has been made in Section 6.1 to the tendency of the reinforcing tapes to be locked by the application of the full internal gas pressure. Many cases, however, have occurred where cables have been removed, drummed and relaid. These operations required care in respect of speed and degree of bending, but in all cases the work was accomplished satisfactorily.

(7.2) Jointing

Jointing is clean and relatively simple, the hand-applied taping following a technique similar to that used on fully-screened solid-type joints. A low-pressure gas test is carried out during jointing to ensure that the plumbs and the O-ring gasketed joints at each end of the pressure sleeve are leak-proof.

The jointing time for single-core 132 kV joints is of the order of 25 hours, and for 66 and 33 kV 3-core joints the times are approximately 28 and 24 hours, respectively.

(7.3) Gas-Charging of the System

After completion of the laying and jointing, gas charging is started from one end of the route, from a battery of nitrogen cylinders interconnected by a manifold feeding into the cable through the 2-stage regulator in the gas-charging equipment. The initial charging pressure is about 50 lb/in^2, and this is maintained until gas continuity is established at the first intermediate charging joint. The feeding pressure is then raised and additional cylinders on a portable trolley are used to inject gas at this intermediate point. Feeding pressure may be raised at the rate of 50 lb/in^2 per hour, provided that there is no pressure differential greater than 50 lb/in^2 per 1 000 yd between charging points.

The time taken for initial charging of a system will be dependent on the type of cable, the length of the installation and the number of intermediate charging points. This initial charging may be carried out progressively before jointing of the installation is complete. If the system is degassed, owing to the need for making a repair, the subsequent recharging operation may be carried out at a considerably increased rate. This is permissible because the pressure sheath has been fully distended and the gas annulus under the sheath enlarged and made more uniform. Under these conditions the time taken for recharging will be of the order of two days per mile of single-core cable and half this time for 3-core cable.

The amount of gas required to charge a cable installation depends on the type of cable. Single-core cables have a gas volume at s.t.p. of approximately 21%, and 3-core cables of approximately 40% of the internal volume of the pressure sheath taken as an empty pipe.

(7.4) Gas-Leak Location

It has already been stated in Section 5.4 that the gas-charging equipment includes a 2-stage regulator which automatically feeds gas into the system should a leak occur. This type of 'open feed' system was introduced only in 1952, and previously all but one of the gas-filled cable installations operated on the 'closed feed' system, which required manual operation of the regulator when, under leak conditions, gas had to be fed into the cable. Most of these older installations have operated very satisfactorily, and this shows that on correctly designed and installed systems subsequent gas leaks during a long service life are rare.

While gas leaks do not occur frequently, means must be provided for their location. A large number of methods exist, and many have been described in some detail in a previous paper.[14] Experience has suggested that the following two methods used in conjunction are generally suitable:

(*a*) Measurement of the fall in pressure along the route, using gauges temporarily attached to the surface boxes at the gas-charging points. This gives the first location as between two charging points.

(*b*) The injection at the nearest gas-charging point of a halogen and the location of the leak position by means of a special probe connected to an electronic halogen detector.

Experience has shown that, apart from leaks due to the defects quoted in Section 9, cable leaks are rare and almost all the minor leaks occur at accessories. For this reason an asbestos-cement probe tube is located at the centre of each joint bay, the upper end of the tube being terminated in a small man-hole fitted with a frame and cover. The probe of the halogen detector may be lowered into this tube in order to locate a suspected leak. In this way, leaks from buried accessories may be found without excavation. A cable leak may be pin-pointed along the cable run in a similar manner, by drilling small holes in the ground above the cable, for use with the probe of the halogen detector.

Several other methods based on rates of flow, the measurement of pressure drop across joints and the injection of radioactive gases can also be used. With these methods, leaks can be located while the cable is maintained in service. The means used are chosen for their suitability to the conditions of an individual case, but the location of a gas leak rarely presents any major difficulty.

Local degassing may be advantageous in order to repair damage to the cable, and techniques have been developed in the field for producing small blockages by the use of a freezing technique. This technique comprises the localized injection of a small quantity of carbon dioxide and the subsequent freezing of this gas within the cable by means of liquid oxygen applied to the outside of the cable in a specially designed bath. Experience has shown, however, that this method is rarely economic in comparison with the partial degasification of the cable in accordance with normal practice.

(8) OPERATIONAL EXPERIENCE

(8.1) General

After some 20 years of experience with the operation of the gas-filled cable system it is desirable to review the results in order to determine, from the incidents which have occurred, whether all design imperfections have been or can be overcome.

(8.2) Electrical Faults

(8.2.1) Joints.

Reference to Table A shows that 31 000 yd of 132 kV 0·4 and 0·6 in^2 single-core double-lead-sheathed cable were installed in 1941–42 for the North-West England region of the C.E.B., between Liverpool and Birkenhead, underneath the roadway in the Mersey Tunnel. On this installation semi-screened bitumen-filled joints of the type shown in Fig. 9 of Reference 1 were used. Owing to errors in jointing practice, the cross-feed pipe from the cable sheath to the expansion dome was tied to the core insulation in front of the stress cone. Several electrical faults arose from this, and the joints were remade. During the examination of these faulty joints it became apparent that the use of a bituminous filling compound in contact with the dielectric within the joint pressure sleeve gave rise to some deformation of the dielectric under rapid degassing conditions. When the joints were remade, therefore, the hand-applied joint dielectric was enclosed within a copper tube which was itself contained within the original pressure sleeve, the annular space between the two sleeves being filled with bitumen compound. The inner copper sleeve was pressurized with nitrogen from the cable itself and was made sufficiently rigid to withstand a collapsing pressure of 250 lb/in.^{2}

Modern joints of the single-pressure-skin type are all of the fully-screened design, and the above-mentioned electrical faults which took place on the earlier semi-screened design cannot recur. No other electrical failures on joints have occurred.

(8.2.2) Sealing Ends.

Several cases have occurred of sealing-end failures on the old type of double-porcelain sealing end shown in Fig. 11 of the original paper.[1] These incidents caused an electrical fault on the system, but they were due to the leakage of gas from the inner pressure-porcelain into the outer normal porcelain, which failed under excess internal pressure. Thus the cause of these faults was pneumatic rather than electrical. From 1948 onwards single-pressure porcelains of the type shown in Fig. 10 have been used. Five cases have occurred where these have fractured in service, though in only two of these was there an immediate interruption of supply. Owing to the destruction of all evidence by the occurrence of the fault, it was impossible to establish with certainty the true cause. It may be said, however, that, since these incidents represent such a small fraction of the number of single-pressure porcelains in service, the faults may be regarded as isolated and not due to defective design.

(8.2.3) Cable.

Only two electrical cable failures have occurred, one on a 132 kV single-core cable and the other on a 66 kV 3-core cable. The former was due to electric-stress concentration resulting from a localized rucking back of the aluminium-core screening tapes during lead sheathing of the cable, and the latter was due to mechanical damage sustained by the cable.

(8.3) Pneumatic Faults

(8.3.1) General.

Gas leakages have occurred from time to time and have been due to a variety of causes which are summarized in the following Sections. Minor leakages from pipework and valves, and occasionally from faulty flat-gasket seals on the earlier designs of accessories, have been excluded from this review. Additionally, gas leakages occasioned by third-party external mechanical damage to the cable have been omitted.

(8.3.2) Leaks in Accessories.

Early designs of accessories used castings for the main pressure-retaining components. Porous castings due to faulty manufacture produced a number of leaks of very small proportions. These leaks occured on installations operating on the closed-feed system and therefore the faulty joint sleeves had to be replaced. Modern designs of joints use mainly prefabricated or extruded pressure-retaining components and thus only a very small number of castings is necessary. Additionally, all accessories are now rigorously gas tested at 300 lb/in^2 under water after a hydraulic test of 600 lb/in^2, and thus the possibility of porosity occurring on installed accessories is reduced to negligible proportions.

Certain initial difficulties due to the use of incorrectly dimensioned components were experienced when the design shown in Fig. 7 was introduced. These, however, were quickly overcome and the design has since proved entirely satisfactory.

(8.3.3) Leaks in Cable.

In the early designs of 33 kV 3-core gas-filled cable, two leaks arose from extrusion defects because the sheaths were extruded under unsuitable lead-press conditions. Leaks also occurred on some of these cables because they were manufactured with a reinforcement comprising wire armour and whipping tapes with no anti-corrosion protection. This construction gave rise to leaks adjacent to the cone-type armour termination at points where the sheath was not adequately supported, and also at other points on the cable where the reinforcement lost its strength due to heavy localized corrosion. More recent designs of cable have a fully compensated reinforcement on both unarmoured and armoured constructions, and in all cases the reinforcement is protected from corrosion by the high-quality anti-corrosion serving.

Apart from the leakages recorded above, which, owing to changes in design, are mainly of historical significance, the following incidents have occurred on current cable designs:

(*a*) Three leaks have arisen from oxide inclusions in the lead-alloy sheath. Two of these were on installations in this country and one on an installation in South Africa. In all cases these leaks were due to the incorrect operation of the lead press. The necessary steps have been taken within the factory to reduce to a minimum the possibilities of a recurrence of this type of fault.

(*b*) One leak has occurred on a 66-kV single-core cable owing to localized stress corrosion of the tin-bronze reinforcing tapes, arising from attack by ammoniacal vapours probably emanating from a sewer. This leak occurred 16 months after installation of a cable, which for a few feet was laid direct in the ground, the reinforcement being protected only by compounded textile servings.

It was known that brass was particularly susceptible to this form of corrosion, and tin-bronze was thought to be almost immune. The occurrence of this incident, together with results of a long and detailed investigation, have shown that, while no copper alloy is immune from this form of corrosion, the provision of the anti-corrosion protection provides a complete and lasting protection against this special form of attack. The lengths of cable concerned in this incident were replaced by similar cables having the full anti-corrosion protection.

(*c*) Five cases have occurred of leaks due to penetration of the lead-alloy sheath caused by disturbances of the reinforcing tapes. In two cases these disturbances were due to mechanical damage during manufacture, and in the remainder they were due to excessive twisting of the cable so that the inner layer of reinforcing tapes was slackened and formed an inward fold which subsequently penetrated the lead-alloy sheath. In two of these cases the twisting of the cable occurred during manufacture, and was due either to inadequate control against twist of the free end of the cable during the reinforcing process or to the application of the inner layer of tapes

with too low a tension. In the remaining case it is possible that the disturbance to the inner layer of reinforcement was the result of excessive twisting of the cable during installation. Apart from this last case, which is considered to be an isolated incident, measures have been taken in the factory to eliminate any twisting of the free ends of the cable during reinforcing and also to apply all the reinforcing tapes with controlled tensions. It is considered that these measures will prevent the recurrence of leaks due to disturbances in the reinforcement.

(8.4) Summary of Fault Experience

Section 8.3 gives details of the faults on the gas-filled cable system which have occurred during the past 20 years. Since the early years must be considered as a development period and to date more than 680 000 yd of the cable are in service, it is considered that this record compares favourably with that for any other high-voltage cable system.

In the case of accessories, almost all the electrical and pneumatic faults are associated with earlier designs which have now been replaced with simpler and more foolproof constructions.

Electrical faults on the cable have been small in number, and all resulted from some form of mechanical damage.

It is considered that pneumatic faults on the cable are few when related to the length of cable installed. All the major causes of these faults have now been appreciated, and it is anticipated that the measures taken are such as to prevent their recurrence.

(8.5) Examination of 132 kV Cable installed in 1937

As recorded in the original paper[1] and also in the Introduction, the first installation of 132 kV gas-filled cable and accessories was made at Wimbledon in 1937.

In 1950 this installation had to be abandoned, since the conductor size was no longer adequate for the capacity of the overhead line with which it was in series. The cable was redrummed and, together with the accessories, was returned to the factory for examination.

The cable and accessories showed no visible evidence of deterioration, and this was substantiated by measurements of the radial power factor, moisture content and compound content on samples from the cable dielectric. Sample lengths of the cable were also subjected to power-factor/voltage and impulse tests, and the results showed that, after 13 years' service life, the cable complied fully with present C.E.G.B. requirements.

(9) FUTURE DEVELOPMENT

(9.1) Conductor

Compacted or segmental conductors are desirable in order to make the most economic use of conductor materials. With such designs, however, difficulties may be experienced in obtaining the necessary compromise between conductor dimensions, flexibility and conductivity. Screening of conductors is still under investigation, but it is possible that it will be omitted on the lower-voltage cables and carbon-paper screening used in the higher-voltage range.

(9.2) Dielectric Materials

With the greater knowledge of dielectric behaviour obtained from cable-model work it is inevitable that improvements in dielectric materials will be made. Many of these will, from the user's viewpoint, be subtle, but should result in the decrease of overall dimensions, owing to the use of higher operating stresses. The production of 3-core 132 kV gas-filled cables is likely to be an obvious short-term result of this type of work.

Effort will be concentrated on the further improvement of impulse performance, and if the a.c. characteristics then limit design stresses, increase of gas pressure will be a natural and simple development. Submarine cables[2] are already operating at 300 lb/in^2, and so experience has already been obtained on the reinforcement and accessory designs with higher pressures. The use of higher gas pressure might well be introduced in association with a pipe-type system.

The pre-impregnated construction lends itself to very interesting possibilities of combining pre-impregnated paper and plastic materials. The most promising combination is that of impregnated paper interleaved with polystyrene. The high breakdown strength and low permittivity of the polystyrene is used to increase impulse strength by improvement of the radial barrier and the a.c. strength by decreasing the stress across the butt gaps. Models made with an interleaved polystyrene and impregnated-paper construction have withstood impulse stresses of greater than 1 600 kVp/cm at 85° C. In the practical construction the interleaved section is used for the inner part of the dielectric until the stress is reduced to the normal safe design stress for impregnated paper alone. At present, the design is limited by the heat stability of polystyrenes available, but the production of improved materials of superior heat resistance is well advanced.

(9.3) Non-Metallic Reinforcement

A major contribution to the total losses of the gas-filled cable arise from the reinforcement and sheath. Some assistance in decreasing these losses can be obtained by using single-point earthing or cross-bonding techniques, but the complete elimination of these metallic components would be the ideal solution. The problem of the reinforcement has been investigated and a number of materials have been considered, of which polyester-resin/glass-fibre laminates appear to be the most promising. After preliminary trials with hand-made samples had been found encouraging, a pilot plant was assembled and gas-filled cable has been reinforced successfully with these materials. Trial lengths are now undergoing an extensive series of tests to determine the long-term chemical, mechanical and physical characteristics of the reinforcement. Commercially the system is very attractive, since it combines an improved current-carrying capacity with a material cost which is cheaper than that used at present.

(9.4) Joint Design

Considerable improvements in mechanical design of gas-filled joints have been made in recent years, but the electrical design has remained static. The joints require a protracted jointing time, and are often—as seen in Section 6.2—the weak link in design tests on miniature systems. A programme of work is at present under way in an attempt to improve this position.

(10) CONCLUSIONS

The gas-filled cable system has now been proved by many years of successful experience and the claims made in the conclusions of the original paper[1] have been vindicated.

The increasing knowledge of the fundamental behaviour of the system as a whole has confirmed the soundness of the original conception and will undoubtedly lead to further technical and economic improvements.

(11) ACKNOWLEDGMENTS

The authors' thanks are due to W. T. Glover and Co., Ltd., for permission to publish the paper and to their colleagues for valuable work performed over a period of many years.

(12) REFERENCES

(1) BEAVER, C. J., and DAVEY, E. L.: 'The High-Pressure Gas-Filled Cable', *Journal I.E.E.*, 1944, **91**, Part II, p. 35.

(2) INGLEDOW, T., FAIRFIELD, R. M., DAVEY, E. L., BRAZIER, K. S., and GIBSON, J. N.: 'British Columbia—Vancouver Island 138 kV Submarine Power Cable', *Proceedings I.E.E.*, Paper No. 2354 S, April, 1957 (**104** A, p. 485).

(3) BEAVER, C. J.: 'Lead Cable Sheaths', *Electrical Review*, 1954, p. 468.

(4) THORNTON, E. P. G.: 'Corrosion Protection of Cables', *Electrical Times*, 1953, p. 843.

(5) SALVAGE, B.: 'The Impulse Breakdown of High-Voltage Cables of the Solid and Gas-Cushion Types', *Proceedings I.E.E.* Paper No. 1468 M, February, 1953 (**100**, Part II A, p. 163).

(6) HALL, H. C., and SKIPPER, D. J.: 'The Impulse Strength of Lapped Impregnated Paper Dielectric', *ibid.*, Paper No. 2025 S, April, 1956 (**103** A, p. 571).

(7) GAZZANA-PRIAROGGIA, P., and PALANDRI, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High-Voltage Cables', *Transactions of the American I.E.E.*, 1956, **74**, Part III, p. 1343.

(8) HALL, H. C., and KELK, E.: 'Physical Properties and Impulse Strength of Paper', *Proceedings I.E.E.*, Paper No. 2024 S, April, 1956 (**103** A, p. 564).

(9) HALL, H. C., and RUSSEK, R. M.: 'Discharge Inception and Extinction in Dielectric Voids', *ibid.*, Paper No. 1618 M, February, 1954 (**101**, Part II, p. 47).

(10) LEVI-CEVITA, T.: *Rendiconte del Circolo Matematico di Palermo*, 1905, **20**, p. 173.

(11) HOWARD, P. R., and BROWNING, D. N.: 'Stranding Effect in Cables', *Journal I.E.E.*, 1955, **1** (New Series), p. 653.

(12) BRAZIER, L. G.: 'Joints, Sealing Ends and Accessories for Pressure Cable', *Journal I.E.E.*, 1946, **93**, Part II, p. 415.

(13) GAZZANA-PRIAROGGIA, P.: 'Sealing Ends for High Voltage Cables to be Connected Direct to Transformers or Switch Gear', C.I.G.R.É., Paris, 1954, Paper No. 205.

(14) BRAZIER, L. G., HOLLINGSWORTH, D. T., and WILLIAMS, A. L.: 'An Assessment of the Impregnated Pressure Cable', *Proceedings I.E.E.*, Paper No. 1484 S, December, 1953 (**100**, Part II, p. 641).

(13) APPENDICES

(13.1) Cable Construction

Conductor.—Copper or aluminium; for single-core cable for all voltages the section is 'died down' circular; for 33 kV 3-core it is oval, and for 66 kV 3-core it is circular up to $0\cdot5\,in^2$ and oval at $0\cdot55\,in^2$ and above, the change point being decided on economic grounds.

Conductor screen.—Two or three layers of metallized paper according to operating stress.

Paper.—$1\frac{3}{4}$, $2\frac{1}{2}$, 4 and 6-mil wood pulp, pre-impregnated to give non-draining dielectric over the complete operating temperature range. Special high-density papers are used for cables in which the conductor stresses are 100 and 110 kV/cm.

Impregnant.—Refined paraffinic jelly.

Core screening.—Copper tape or metallized paper applied with an overlap.

Lead-alloy sheath.—0·1% antimonial alloy is a standard, but alloys E or B are used for conditions of moderate and severe vibration, respectively.

Reinforcement.—For single-core cable it is 1% tin bronze; for 3-core cable it is mild steel, with 1% tin-bronze for improved current ratings. All tapes are applied in four layers at the critical angle such that provision is made for longitudinal and circumferential components of the pressure load. The outer and inner two layers are applied in reverse directions. All tapes are applied with a small gap on a single-, double- or treble-start principle to limit individual tape widths to 2 in, in order to maintain a satisfactory bending performance.

Anti-corrosion serving.—The impermeable layer* consists of a rubber sheath comprising four layers of specially formulated tough-rubber tapes applied in the unvulcanized condition between a bituminized-cotton tape and a carbon-impregnated cotton tape. The rubber tapes are vulcanized and bonded by the application of heat. The carbon-impregnated tape serves as an outer electrode for the electrical testing of the rubber sheath.

(13.2) Cable Characteristics

Conductor stress	75 kV/cm at 33 kV 85 kV/cm at 66 kV 90 or 100 kV/cm at 132 kV 110 kV/cm at 275 kV
Dielectric thermal resistivity	550 thermal ohm-cm
Maximum operating temperature	85° C
Permittivity	2·9
Power factor at working voltage	0·0040 at 20° C 0·0030 at 50° C 0·0035 at 90° C
Nominal gas pressure	$200\,lb/in^2$
Minimum operating gas pressure	$180\,lb/in^2$
Maximum design gas pressure	$250\,lb/in^2$

* The protection of the reinforcement by a second lead sheath was discontinued in 1950 for economic reasons.

DISCUSSION ON THE ABOVE PAPER

Before the SUPPLY SECTION 17*th December, the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER 21*st October, the* SHEFFIELD SUB-CENTRE *at* SHEFFIELD 19*th November*, 1958, *and the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE 12*th January*, 1959.

Mr. F. J. Lane: Reference to discussion of the paper by Beaver and Davey indicates a somewhat sceptical reception for the gas-filled design, and it is the main object of the present paper to show how faith in the original design has been justified by a very satisfactory record of performance in service and of competition with other designs. I recall that when plans were being prepared for an a.c. cable crossing the English Channel, this type of cable and one other were selected for trial and, although it was said of this cable that it operated at lower stress than its competitor and made less efficient use of the materials, severe and lengthy tests proved it to be the more acceptable proposition for the Channel crossing.

When Sir John Hacking (then Mr. Hacking) opened the discussion on the earlier paper and drew attention to the basis on which the Central Electricity Board made its selection from available designs of equipment in the following terms: 'Where alternative designs are technically sound and capable of meeting the service conditions, the selection between them will be governed entirely by economic considerations.' This attitude has always been strictly maintained, and, coupled with insistence on a rigorous testing procedure, has ensured continuous competitive development amongst the various cable designs. Adequacy of performance and competitive prices are the determining criteria,

and by these tests the gas-filled cable has shown itself well worthy of a good position in the field. Taking note, however, of a difference of 15 years between the presentation of the two papers, we are entitled to ask, not perhaps as Sir John did—as to the 'comparative costs of the various alternative designs . . . for the different voltages'—but rather to what extent the changes outlined in the paper have reduced the cost of manufacture. Are we not justified also in feeling that, although this cable is shown to be competitive with other types, it should be very much cheaper because of the elimination of the length-by-length vacuum impregnating process?

At the time of the original paper there was considerable emphasis on the importance of a second lead sheath which is not now considered necessary, and there were other references to possible future developments, regarding which the authors should, for the sake of continuity, make some comment.

I hope that the next 15 years will see much more progress in the use of the newer materials as foreshadowed by the authors, and in simplification of accessories where success in operation may be dependent as much on reliable workmanship as on design.

Mr. C. C. Barnes: The $0 \cdot 3\,\text{in}^2$ gas-filled cable installed at Wimbledon in 1937 was designed for a maximum stress of 85 kV/cm (minimum radial thickness of insulation = 0·61 in), the 1954 $0 \cdot 3\,\text{in}^2$ Woolwich–Eltham cable for 90 kV/cm (0·56 in minimum insulation) and for the recent Belvedere–Sydenham cable a gas-filled design for 100 kV/cm was offered ($0 \cdot 6\,\text{in}^2$ conductor with 0·41 in insulation). The C.E.G.B. accepted this highly stressed design only after it had complied fully with their type-approval tests. Briefly these tests on pressure cables necessitate a miniature system of cable with all its associated accessories and sealing ends which is subjected to (*a*) 20 loading cycles at 1·5 times normal working voltage, and for the last three hours of each current loading period the maximum conductor temperature is maintained at not less than the guaranteed maximum temperature plus 5° C, and (*b*) hot impulse-withstand test. For 33, 66 and 132 kV systems the peak impulse withstand levels are 194, 342 and 640 kV respectively. Where possible, the loading cycle test and impulse test are made on the same assembly.

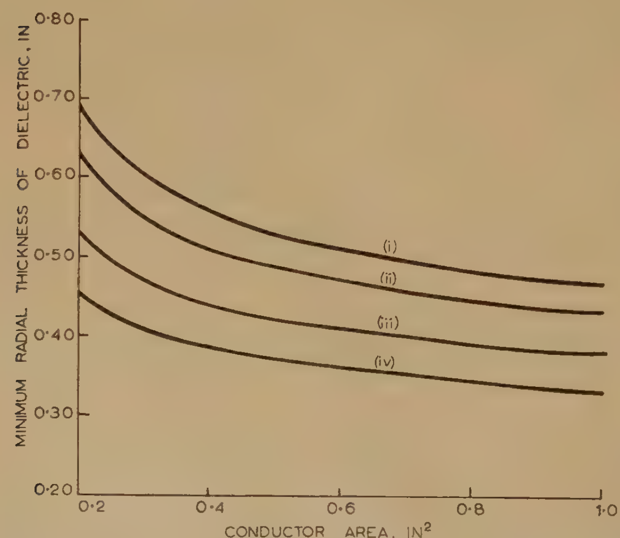


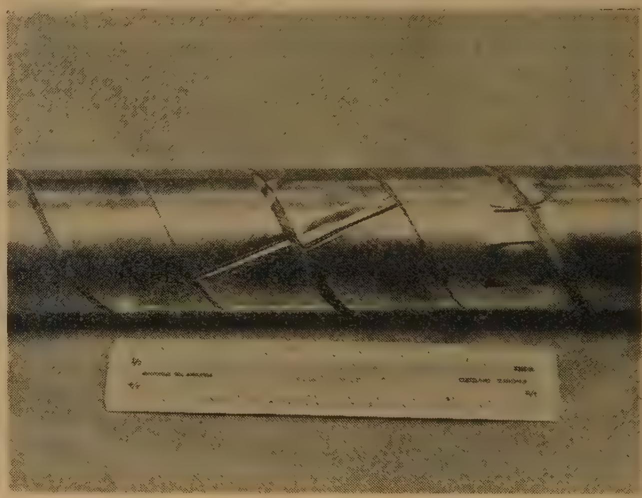
Fig. A.—Minimum radial thickness of dielectric for single-core 132 kV gas-filled cable.

Maximum electric stresses:
(i) 85 kV/cm
(ii) 90 kV/cm
(iii) 100 kV/cm
(iv) 110 kV/cm

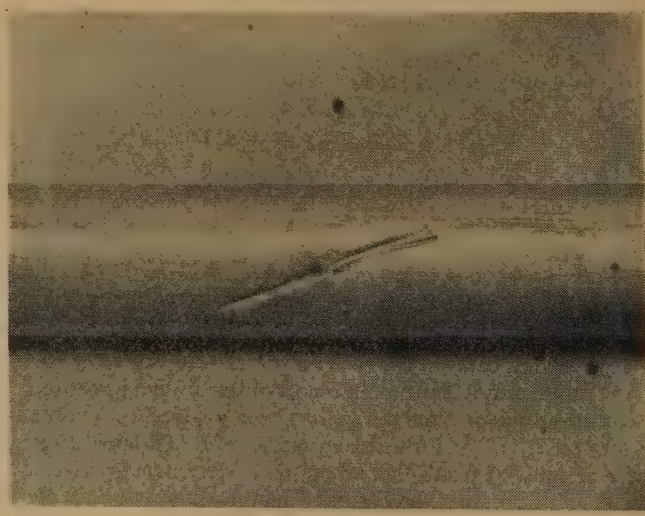
Additional tests are for cold power-factor/voltage variation and dielectric thermal resistance, a mechanical test on the metallic reinforcement and a saline-bath test on the anti-corrosion covering. A range of sample tests are also made. These tests are complementary to the earlier long-term design tests made by the cable makers as part of their own development work. Type tests have greatly improved the quality of pressure-cable systems.

Only one fault occurred on the 1937 Wimbledon cable and this was due to mechanical damage during trench excavations in July, 1939; nevertheless the dielectric of that cable was lapped slackly and this resulted in a relatively low surge strength and high thermal resistivity of the dielectric. The thermal resistivity of the Wimbledon cable was 700 thermal ohm-cm, compared with 550 for modern gas-filled cables.

In Section 13.2 the authors recommend a maximum electric design stress of 90 or 100 kV/cm at 132 kV. Recent years have shown a steady increase in the design stress accepted by users, but type-approval tests, however well planned, do not provide a complete substitute for successful service experience; and for buried cable systems at 132 kV, where such cables are to-day made and installed in very long lengths, stresses above about 100 kV/cm should preferably be installed on a 'field trial' basis.



(i)



(ii)

Fig. B.—Effect of faulty reinforcement.

(i) Defect in reinforcement.
(ii) Resultant defect in lead sheath.

The costs associated with any faults are high, and Fig. A shows decreasing economic advantage with increasing electric stress.

Until very recently a standard feature of the gas-filled system has been the use of a bituminous filling compound for the sealing ends, but in Section 5.1 it is stated that, for 132 kV 100 kV/cm service, an oil–polyisobutylene filling is used. This is an important design change and its success presumably depends on the continued integrity of the taped poultice; the authors' views on this feature will be welcomed.

Section 8.3.3 (*c*) refers to reinforcement fault incidents (Fig. B). Five cases are reported, but a number of further incidents have occurred more recently. For the successful design and utilization of the metallic reinforcement on gas-pressure cables operating at a nominal pressure of 200 lb/in^2, the following factors require study:

(*a*) The material used, its thickness and 'temper'.
(*b*) The method of application and the control of this operation on the reinforcing machine.
(*c*) The nature of the installation conditions, i.e. number of bends, extent of handling, length of pull, etc.

In view of the vital importance of the behaviour of reinforcement on a pressure cable, the authors' views on the basic cause of this trouble and the remedies they have put into effect will be welcomed. Furthermore, the long-term integrity of any metallic reinforcement is wholly dependent on the type of overall protection adopted. For expensive pressure cables and important circuits carrying heavy loads, a high-grade covering of the type detailed in Clause 20 of the C.E.G.B. C.4 Specification utilizing a 40 mil impermeable layer is essential.

Mr. C. T. W. Sutton: It is not easy for a contemporary cable maker to discuss a paper which deals principally with the results of service experience over a number of years. It is possible to raise obtuse technical points or to indicate subtly where the design is weak, but this approach could be irritating and any criticisms would be counteracted by emphasizing 20 years' successful service life.

This cable was developed after Höchstädter had successfully used gas pressure to suppress ionization—the compression-cable principle. It is unique in that it does not follow normal cable mechanics, relying on gas pressure contained in the dielectric in a definite pattern to prevent breakdown. The cable maker must still rely on a paper dielectric to match the continual 'doubling up' of voltages.

We have tried to understand more clearly the properties of materials to utilize them more effectively, to simplify accessories etc., and to improve economics. The paper shows that considerable progress has been made in this way, but more information would be useful on the choice of compound. With hand taping why are Terylene tapes included? Is it possible for the hand-applied dielectric to be disturbed with loss of gas in the joint sleeve? Is this the reason for using a hollow conductor for submarine cables only? Must bitumen still be used?

It is unfortunate that 10 kV d.c. is becoming mandatory for all types of corrosion protection, since the voltage bears no relationship to service conditions and was necessary for one particular coating. Further thought should be given to this matter to avoid large future expense. The tests should be related to the type of protection used.

With reference to future developments, most of the suggestions can be applied to any contemporary design. Can it be assumed that gas pressure will still be retained when polystyrene is incorporated?

Mr. L. H. Welch: Until about four years ago the solid-type 33 kV cable was cheaper than the various pressure-control types capable of carrying the same load. The position is now reversed and until recently the gas-filled cable was the cheapest of the pressure-control types. However, a new type of cable, which is sometimes known as 'gutless' has now been put on the market, and this is cheaper still. Not a great deal is known about the behaviour of this latest cable, but it must be of considerable interest to all users. The L.E.B. experience of the gas-filled cable is quite satisfactory, but this only covers a few years and we do not know whether these various types of pressure-control cable will last at least 50 years. 6 kV cable laid early this century is still functioning satisfactorily and has shown that a 50 years' life is possible. Unfortunately some oil-filled cable laid about 20 years ago has been disappointing: large cracks have developed in the lead sheath, and already a considerable length has had to be replaced; it would appear that this process will continue and its maximum life is not likely to exceed 30 years. This immediately raises the question of what precautions are taken during manufacture to avoid troubles such as these described in Sections 8.3.2 and 8.3.3. Can we look forward to sufficient care being taken and sufficient controls being introduced to ensure that these relatively minor manufacturing faults are no longer allowed to occur? What precautions do the manufacturers take to ensure that such faults do not occur, and could the authors give some assurance that these precautions are adequate? For instance, it would appear reasonable to suppose that the machine for impregnating the paper should operate in an air-conditioned and dust-proof room, and there is urgent need to avoid repetition of troubles which have been experienced.

An Area Board designs its transmission system to make use of the cable for as long as it will last, and does not expect to have to dig it up and replace it by a larger size; consequently Area Boards are urgently in need of assurance that adequate precautions are taken during manufacture, so that a good design is not spoiled by faulty detail work.

Mr. P. M. Hollingsworth: It is rather a pity that the authors were content to refer merely to one very unrepresentative type test to support a paper entitled 'Design and Performance'. This is the one example where a comparison can be made between model and cable tests, namely on hot impulse strength; it is interesting to note from Table 3 that the model gave a mean breakdown level of 830 kV/cm but that 940 kV/cm was obtained in the type test and even then the cable did not fail. One further point on parameters: the permittivity of the cable is given as 2·9 and the thermal resistivity 550 thermal ohm-cm. Now in l.v. mass-impregnated cables with small compound content an average permittivity is 3·0 and the E.R.A. have adopted for calculation a resistivity of 750 thermal ohm-cm. Can the authors reconcile their figures?

The performance of the gas-filled cable will be watched with interest, and impulse strength is one vital factor. The high-temperature performance, taking the figure given in the type test, is good but not high by modern standards. The big difference between hot and cold levels in Table 3 indicates that a different compound and also a greater compound content might be beneficial. Is this a change of practice likely to occur? Surely, also, thin tapes must be adopted ultimately and their advantages exploited by improved lapping methods.

The prospective use of plastic materials is an interesting development, but the need to combine them with impregnated paper is presumably for economic rather than technical reasons.

The authors briefly mention increasing reinforcement strength to permit higher gas pressure in a.c. cables. This can be costly and may involve more risk of joint troubles. It is all very well to cite the performance of a submarine cable which has no joints. Matters may be very different for a land cable with four joints to the mile.

One thing which surprises me is the authors' failure to use

aluminium for sheathing. In my opinion it is far the best form of sheath for self-contained gas-pressure cables, eliminating, as it does, the costly and complicated reinforcement necessary for lead sheathing. With the high-quality protective coverings now available the corrosion hazard is removed and jointing techniques are straightforward and well proven. My own company has more than 100 miles of aluminium-sheathed gas and oil cables in service at voltages up to 132 kV. I thus commend aluminium sheathing for the authors' consideration, at any rate pending any major step forward with non-metallic reinforcement.

Dr. A. N. Arman: Of the various gas-pressure solutions to the non-ionizing cable problem, the gas-filled one has always seemed by far the best, inasmuch as its characteristics remain constant throughout its life.

The initiation of breakdown is due to gaseous ionization in the papering spaces. The limiting a.c. stress is thus the ionization inception voltage, but this can be considerably exceeded under impulse conditions without total breakdown because of the barrier effect, which becomes less effective at elevated temperatures. Information regarding the fatigue effect when this type of insulation is subjected to numbers of impulses in excess of the normal 10 positive and 10 negative would be useful. The impregnated paper is subjected to bombardment at each impulse, and cumulative deterioration of the dielectric is likely, increasing with temperature. With individual impulses of longer duration (such as switching surges), a lower impulse strength is to be expected. Although usually of lower voltage than lightning surges, the cumulative effect of fatigue will be greater with this type of surge. Some information on this would be of interest.

The present limiting design factor is the a.c. ionization inception stress and not the hot impulse strength. Improvement in the latter, as suggested in Section 4.3.2, will not be of much use unless it is accompanied by an increase in the former. This can occur if the permittivity of the impregnated paper can be materially reduced, and this is not likely to be achieved by additives to the impregnant. It would appear that advantage could be taken of increased gas pressure, even with the present type of impregnated paper.

In connection with the loading-cycle test, taken eventually to 140° C, how many cycles were carried out at each current step and how many steps were made?

Mr. A. Haddock: Sheffield has 37 miles of this cable in service, installed at a steady rate since 1940; it is mostly of 3-core $0\cdot4\,in^2$ construction and is fully loaded. In 18 years of operation we have had no electrical breakdown of cable, either in service or on test. We have had two breakdowns of joints in service, both of the terminating type shown in Fig. 9, and two straight joints have failed on over-voltage test. We have had trouble with gas leaks. With the early designs it soon became apparent that impregnated hessian serving was insufficient to prevent corrosion of the steel-tape armouring. During an air raid, damage was caused to the serving of a cable which was above ground in an industrial neighbourhood. The steel tape corroded and the lead burst in a few weeks. With this design the life of the cable was the life of the serving, which led to the use of a second lead sheath over the armouring. This provided adequate protection, but was costly and was soon replaced by rubber and hessian serving and finally by the present design.

I am still not satisfied that the present design provides the standard of protection desired, which must be good enough to enable cables laid in corrosive ground, and subject to damage on installation and afterwards, to last for 50 years.

The gas-filled cable enables a higher maximum rating per circuit at a given voltage to be achieved than most other designs. This is a very real advantage in a congested locality, and reduces the circuit-breaker cost per kilovolt-ampere transmitted, particularly important with fully-loaded short feeders.

Monsieur R. A. Tellier (*France*): The gas-filled cable has not yet been used on the French high-voltage systems. This does not mean that its merits are not appreciated, and it is quite possible that such cables will find an application in our country.

Our main opportunity to become acquainted with this type of cable was the cross-Channel test programme which was initiated some years ago, when an a.c. link was considered, and which led to the final selection of this cable technique for the project involved. Several samples of gas-filled cables were tested at the Fontenay Research and Testing Centre, and my two main remarks are based on the experience gained from these tests.

The authors do not seem to consider as an essential precaution the lapping of pre-impregnated paper tapes in a conditioned atmosphere, even for the highest cable voltages. However, during the stability tests carried out at Fontenay on 132 kV cable samples connected to the 225 kV system (test stress of about 150 kV/cm), it was noted that the British and French cables manufactured in normal factory atmosphere rapidly failed (after 50 or 100 hours), whereas a length of French cable manufactured in a conditioned atmosphere was subjected to the same test conditions for about 1800 hours before a failure developed in a flexible joint. This cable, which was subsequently shortened, has now been on test for approximately 10 000 hours. A sample of British cable which, so far as I know, was also manufactured in a conditioned atmosphere has also been on test for about 8 000 hours without failure, apart from that of a flexible joint.

My second point relates to the use of a sulphur-hexafluoride/nitrogen mixture as pressure medium for gas-filled cables. Investigations carried out in France have shown that with such a mixture the breakdown stress of this type of cable can be substantially increased.* The mixture does not seem to have any bad effect on the long-term performance of the cable, since the sample which has been on test at 150 kV/cm for 10 000 hours is partially filled with sulphur hexafluoride. The use of this mixture has also permitted the testing of short samples of 132 kV gas-filled cable at stresses of about 250 kV/cm for several hundred hours, by connecting them between the phases of the 225 kV system.

Dr. F. J. Miranda: The authors give no indication of the scatter from mean values of impulse strength for their experiments on capacitors and cable models. Furthermore, with the exception of the experiment reported in Table 3, impulse strengths have been measured only at ambient temperatures. This seems to be a very serious gap in the authors' investigations. However, the data given can be used to determine the probable electric strength of a gas-filled cable.

Consider a perfectly screened cable conductor of about $\frac{1}{2}$ in diameter (equivalent to $0\cdot2\,in^2$ section) lapped in the region of high stresses with $1\frac{3}{4}$-mil high-density paper and 65/35 registration. Table 6 gives a mean impulse strength at ambient temperature of 1 180 kV/cm. With a scatter from the mean of $\pm5\%$ and a reduction for temperature of, say, 20%, the probable impulse strength of the cable is about 900 kV/cm. If account is taken of stress relief due to denser papers near to the conductor, this is in fairly close agreement with the value quoted in Section 6.2 for a 132 kV 100 kV/cm (nominal) cable. For a cable of $1\cdot0\,in^2$ section, according to Table 4, there would be a reduction of about 10%, i.e. a gradient at breakdown of the order of 810 kV/cm. In both cases the a.c. breakdown gradient is 190 kV/cm (see Tables 4 and 6).

Let us now compare these figures with those obtainable with oil-filled dielectric. A large number of tests on cable models

* ALLARD, G., and DEVAUX, A.: 'Câbles à haute tension avec pression gazeuse à base d'hexafluorure de soufre', *Bulletin de la Société Française des Éléctriciens*, 1957, 7, p. 603.

have shown that, with the right quality of paper and 70/30 registration, the minimum value of impulse strength is 1 250 kV/cm, and even with a 50/50 registration it is 1 150 kV/cm. The a.c. strength exceeds 350 kV/cm. As is well known, these values are independent of temperatures well above the normal working range. These values show that, for the same factor of safety on impulse and a much larger factor of safety on a.c. stress, an oil-filled cable can be designed with a working stress about 25% higher than that of a gas-filled cable.

My company has, in fact, manufactured a 3-core 0·6 in² 132 kV cable with a design stress of 125 kV/cm, and an assembly which included all accessories (straight, trifurcating and stop joints, splitter box, outdoor and oil-immersed sealing ends) has been subjected to all the tests of C.E.G.B. Type Approval Specification C.28. Before and after each test the assembly was subjected to a voltage of $2 \cdot 5\ V_0$ for 24 hours. The impulse test was limited to 660 kV, corresponding to 1 090 kV/cm. The same assembly was then subjected to an identical series of tests at 115° C without breakdown. Again the impulse test was limited to 660 kV. This assembly has now been subjected continuously for about a month to twice working voltage at an average conductor temperature of approximately 120° C. These results prove amply the soundness of the 125 kV/cm 132 kV oil-filled cable system and therefore confirm the validity of our conclusions from cable model tests.

Mr. E. H. Ball: Comparing the design stresses for accessories given in the paper with those suggested by Brazier in 1946, I find that the maximum longitudinal stress in joints, though still low, has been increased from 2·0 to 3·0 kV/cm. The maximum longitudinal stress in sealing ends, however, has been reduced from 2·6 to 2·0 kV/cm.

This appears somewhat contradictory, but, in fact, because of the difficulty of calculating the longitudinal stress accurately and also of producing the correct shape of profile in practice, these longitudinal design stresses are no more than a guide which, when applied in conjunction with simplified methods of calculation of the profile shape, has been found to produce satisfactory designs. Have the authors any experimental evidence of the impulse and a.c. strength of their joint dielectric with longitudinal stressing?

With regard to the maximum radial stress permitted at the lip of the stress control of sealing ends, does this mean the radial component of the actual gradient at this point or simply the stress which would exist at the outer electrode of coaxial cylinders of diameter equal to the conductor and the lip diameter of the profile?

The authors use a semi-flush ferrule, presumably of the type described by Davey,* in which the conductor is hydraulically compressed to receive the ferrule which is thus semi-flush with the conductor surface. Can this principle be applied to compacted conductors, to conductors of shaped cross-section, and to a joint between conductors of unequal section?

Finally, the elimination of filling compound from the joint sleeve increases thermal resistance and may cause overheating in the joint. Longitudinal conduction of heat will mitigate this effect, but I notice that the thermal-stability test described in Section 6.2 failed in the joint at a cable conductor temperature of 140° C. Have the authors measured the temperature at the ferrule of the joint under these conditions?

Mr. B. Webb Ware: The maximum stresses at the conductor seem to fall very neatly in ascending scale from 75 kV/cm at 33 kV up to 110 kV/cm at 275 kV. This looks very logical but needs explanation. For example, when considering tenders for a comparatively minor system operating at 132 kV one feels that a design stress of 110 kV/cm at the conductor cannot possibly be considered; however, for 275 kV cables connecting the whole output of a large atomic-energy station to the Grid a maximum stress of 110 kV/cm for the gas-filled design or 130–150 kV/cm for other designs is quite acceptable. The only available explanation is that it is not practicable to do anything else at 275 kV, which seems unconvincing. I think that the importance of unqualified stress is being overemphasized and that mechanical considerations are the main criteria in practice, for a given operating voltage and conductor diameter.

Mr. R. S. Orchard: I am glad to see the importance which the authors place on performance during bending tests. There is often talk these days of dropping this test, certainly at the lowest voltages, merely because cables rarely, if ever, fail it. Nevertheless, examination of cables after bend tests by both the manufacturers and the supply engineers contributed greatly to improvements in the methods of manufacture of cables, and I believe that it should be retained at all voltages.

Are the authors satisfied with their figure of 0·38% for the moisture content of the insulation at any service voltage or any maximum electric stress, or are there occasions where special measures should be taken to control the moisture content of the atmosphere during the paper-lapping process?

Do the authors favour any programme of investigation into the long-term behaviour of high-grade corrosion-resistant outer covering while in service, possibly by the measurement of leakage current or a reduced-voltage test at intervals during the life of selected cables?

Since solid-setting compound in sealing ends at other than the lower voltage has long been deprecated, it seems undesirable to use it in the gas-filled cable. Liquid oil/polyisobutylene is now used as a filling compound for some sealing ends, so the original difficulty of preventing compound migrating down the cable has presumably been overcome. Why should it not now be used for all sealing ends?

The authors suggest that the a.c. characteristics might limit design stresses in gas-filled cables but in some current specifications there is no test which indicates limitation of performance under power-frequency conditions. The practice has been to alter the routine voltage to suit the pressure cable concerned; thus, if the a.c. design stress increased, the routine test voltage would presumably be reduced accordingly. The same thing occurs for the loading-cycle and thermal-stability type tests. If users wish to check that the power-frequency breakdown stress in the cable and accessories shows an adequate factor of safety over the stresses in service, it is desirable to include a carefully selected voltage type test on either the 15 min basis still used in some specifications or the Continental basis of a 24-hour test.

The present tendency of manufacturers to offer cables with higher maximum stresses under service conditions necessitates, not only a check on the 50 c/s performance, but a corresponding improvement in manufacturing technique and accessory design.

Dr. B. Salvage: Beaver and Davey* gave the impulse strength of the gas-filled cable as 800 kV/cm, presumably at ambient temperature, whereas the authors describe a test in which a gas-filled cable, heated to a maximum conductor temperature of 85° C, withstood impulse stresses up to 940 kV/cm without breakdown. It would seem that this increase in impulse strength has been achieved by modifying the characteristics of the paper, but little information is given on this subject beyond the formula in Section 4.3.1. The impulse strength derived from this formula is nearly twice that of a cable, so the formula presumably refers to plain sheets of paper and ignores phenomena in the butt-gaps of a cable dielectric. The temperature to which the formula

* DAVEY, E. L.: Discussion on 'An Assessment of the Impregnated Pressure Cable', *Proceedings I.E.E.*, 1953, **100**, Part II, p. 655.

* BEAVER, C. J. and DAVEY, E. L.: 'The High-pressure Gas-Filled Cable', *Journal I.E.E.*, 1944, **91**, Part II, p. 35.

applies is not mentioned. In the discussion on the paper by Hall and Skipper,* one of the present authors stated that, with the gas-filled form of dielectric employing an extremely viscous impregnant at ambient temperature, he had found no effect of the density of the paper on the impulse strength, yet the formula in the paper shows that the density is of primary importance. Does this mean that the formula applies to elevated temperatures? Can the authors indicate the relationship between the impulse strength of the cable and the impulse strength and physical properties of the paper?

Beaver and Davey quoted 700 thermal ohm-cm for the thermal resistivity of the cable dielectric, whereas the authors report 550 thermal ohm-cm. Since the permittivity is unchanged, these figures appear to be inconsistent. How has this reduction in thermal resistivity been achieved?

Mr. C. M. Mitchell: The 132kV gas-filled cable installed in 1942 through the Mersey Tunnel was one of the first of any length to go into service after the Wimbledon cable. It consisted of three single-core cables laid in trefoil formation and ran from Clarence Dock, Liverpool, to Birkenhead, a distance of some six miles, one mile of which was in the air duct of the tunnel itself. The gas-filled cable was chosen for this route for two main reasons. First, it contained the pre-impregnated dielectric, and therefore the use of barrier joints in the depths of the air duct was avoided. Secondly, it was considered inadvisable at that time to install in the tunnel any form of oil-filled cable, however remote the possibility of fire might be. In fact, the tunnel authorities insisted on the use of a fireproof serving. The cable was rated at 100 MVA and consisted of two cross-sections in series, $0\cdot6\,\text{in}^2$ for the five miles or so, where the cable was buried and the thermal resistivity of the soil had to be considered, and $0\cdot4\,\text{in}^2$ where it lay on brackets in the air duct itself.

There were already three 3-core 33kV cables in the air duct, and it had originally been intended to install a further similar set, but owing to the greatly increased demands on the Board's transmission system during the war, the decision was taken to install the 132kV cables.

It is interesting to note that, in an effort to discover why trouble occurred at the joints, γ-rays were used to radiograph some of those which had not broken down, disclosing such faults as a displaced cross-feed pipe and voids in the compound. As a result, a new design of joint was developed which has since proved satisfactory.

In 1952 it was decided to install a reactor in series with the cable at the Birkenhead end, and rather than run a new length of cable from the last joint, it was decided to divert the last length of cable from the sealing ends in the substation to the reactor. The advisability of moving a cable was doubted, owing to the possibility of damage resulting from the locking action of the reinforcement tapes after ten years of service, but the confidence placed in the cable at the time was fully justified and it was diverted and energized in 1953.

Mr. O. S. Johnson: The design of all pressure-type cables for voltages up to and including 132kV is controlled by the need to meet an impulse withstand requirement fixed in this country by the rather arbitrary formula $45\,\text{kV} + 4\cdot5\,V$, where V is the nominal system voltage. For 132kV systems the peak withstand voltage derived is 640kV. There is little evidence to show that surges incident on the cable approach this value, and it seems appropriate to consider the effect of a reduction of this level to say 550kV, as in America and specified in the draft I.E.C. specification for oil-filled cables. Such a reduction would permit higher working stresses, and the effect of this on cable dimensions can be appreciated by considering $0\cdot2\,\text{in}^2$ 3-core 132kV cables at various stresses. At 100kV/cm the overall diameter would be approximately $4\cdot3$ in, at 125kV/cm it would be $3\cdot7$ in; a reduction of impulse withstand level to 550kV would enable the overall diameter to be reduced to $3\cdot3$ in, thus resulting in a very large saving in capital investment on major schemes.

If the C.E.G.B. should modify their present impulse withstand requirement, this would open the way to still higher working stresses. As these are increased, the margin between working stress and a.c. breakdown stress is obviously reduced. The paper shows that it is unnecessary to have a very large margin in order to obtain satisfactory service. This fact should encourage acceptance of higher working stresses in other types of cable of intrinsically greater a.c. strength. I recently saw a length of 132kV oil-filled cable withstand successfully for six hours the application of a voltage corresponding to a maximum stress of 520kV/cm. r.m.s.

Since it would have enlarged our knowledge regarding the necessary margin between a.c. working stress and breakdown strength, will the authors provide data on the a.c. breakdown strength of gas-filled cables, both before and after repeated gassing and degassing, and state whether this process has any effect on the impulse withstand strength?

I note from Fig. 1 that metallized paper and copper tape are apparently interchangeable as core screening. Is the copper tape used in preference to metallized paper for any reason other than to improve the current rating, and what proportion of cables are made with the two types of screen? The drawing also shows the c.w.f.t. binder immediately over the cable sheath. Is this usual practice? If not, in what circumstances is it essential?

Mr. A. M. Morgan: The model tests show that the effect of gas pressure on cable performance is critical. This hazard must be met with any cable with gas in the dielectric. With a pressure variation from 0 to $250\,\text{lb/in}^2$, the discharge inception stress has been shown in Fig. 6 to vary by a factor of 5 : 1 and the impulse strength by 3 : 2. The limits of gas pressure for operation are therefore of great importance, and although they are clearly stated in Appendix 13.2, the main text contradicts them. The Appendix states that minimum operating pressure is $180\,\text{lb/in}^2$, while Section 5.3 quotes $125\,\text{lb/in}^2$. The discharge inception stress at $125\,\text{lb/in}^2$ is about 30% lower than that at $200\,\text{lb/in}^2$. I suggest that the authors can recommend operation at $125\,\text{lb/in}^2$ only when the conductor stress is low.

It is inferred in Section 9.2 that cables may be operated at $300\,\text{lb/in}^2$ nominal pressure. The maximum gas pressure is generally limited by the mechanical strength of the pressure porcelains. Generally, the maximum hydraulic pressure test which can be tolerated for a single-pressure porcelain is $600\,\text{lb/in}^2$. British Standard requirements limit the maximum operating gas pressure to $300\,\text{lb/in}^2$. Allowing for an average temperature rise of 65°C in the dielectric, the maximum nominal operating pressure is $245\,\text{lb/in}^2$. The installation quoted by the authors to be operating at $300\,\text{lb/in}^2$ is one in which the pressure variation is small, owing to the small temperature variations.

When considering the failures of single porcelains it must be noted that experience with a similar number of sealing ends, as reported by Brazier, showed no failures. Some 200 sealing ends for compression cables have operated at the same pressure without failure.

It is interesting that the authors are considering a pipe-type system. Since 1932 a pipe system has been used for gas compression cable with satisfactory service experience, using a fully impregnated dielectric with electrical properties at least equal to those of oil-filled cables, and superior to that proposed by the authors.

Mr. C. H. Gosling: Most cable of this type has been laid

* HALL, H. C. and SKIPPER, D. J.: 'The Impulse Strength of Lapped Impregnated Paper Dielectric', *Proceedings I.E.E.*, Paper No. 2025 S, April, 1956 (103 A, p. 571).

in London since 1952, and from Table 1A it would seem to comprise some 40% of all the cable in the country at the moment.

Mr. Barnes points out that 10 kV/cm increase in stress at the higher levels yields very little in respect of economic saving. My experience has been that a close watch on the methods of installation and site costs could often yield far greater economies than any such increase in stress. In this respect, for the Finsbury Market to Holborn cable it was suggested that nine sections should be laid; with a little persuasion we managed to install only seven and save two complete joint-bays—a saving equivalent to some 20 kV/cm increase in stress.

It is important that there shall be full collaboration between the designers of cables and those who install them. This applies both to the economics of the installation and the completion of a technically sound system. In respect of economics, two points come to mind. First, with the increasing cost of labour on the site, a substantial armouring over the anti-corrosion serving of 3-core cables may be advantageous rather than the importation of sand or other suitable material, particularly in remote areas. Secondly, that a hollow core for land use may be economic in some instances to reduce the period of initial gassing and avoid the need for sectionalizing long systems. This would also obviate the difficulty of reduced pressure at the point of damage during gas-leakage conditions.

The 10 kV d.c. test on anti-corrosion serving was developed as a result of troubles in London and has proved invaluable in detecting mechanical damage to cables after installation. This value was chosen after several tests on a particular cable showed that the punctured serving could withstand 8 kV and remain undetected. The value of 10 kV should therefore be kept under review, since with increased serving thickness cables could pass this test, damaged or undamaged.

Finally, with regard to sealing-end design, as stated in Section 8.2.2, five cases of failure occurred. It may be taken that the cause was mechanical in at least three. I suggest that a contributing factor of these failures was the solid connection of the conductor to the connector ring without a flexible joint. The mechanical force due to the conductor expansion will augment the tensile force exerted on the porcelain by the gas pressure.

Mr. P. A. Raine: The figures quoted for moisture content, together with the impressive performance of this type of cable, lead to the conclusion that a content of 0·35% is quite satisfactory at the operating stresses employed. I welcome a statement of this nature, because it is very useful to have correlation between moisture content, power factor and performance.

The precise free-moisture content of any fibrous cellulisic material is and always has been a point of contention. Therefore, when one quotes figures and attaches to them the degree of importance attributed in the paper, it is rather important that one should state precisely what is meant. I note from Section 4.5.2 that all measurements were made using the Karl Fischer technique and that samples were taken from the cable ends. But presumably this method was used for all other moisture determinations as well, and an impression is thereby created that it is an absolute referee method. The Karl Fischer technique is excellent for determining the amount of moisture in a solution, but its accuracy depends entirely on how the moisture is transferred from the piece of impregnated paper into the solution. The paper would thus be improved by some description of, or at least a literature reference to, the method employed.

Mr. W. G. Hawley: In determining the properties of their special dielectric the authors rightly emphasize the importance of the cable model technique. It is a pity that parts of this Section leave one in some doubt as to whether single papers in a flat electrode system or lapped cable models are in question; but I surmise that Fig. 3 refers to single sheets of pre-impregnated paper, since the maximum impulse strength obtainable is only about 1 750 kV/cm. This figure falls short of the 2 000 kV/cm which I have obtained on 4-mil paper impregnated with a viscous compound, measured between specially-shaped electrodes immersed in a bath of the same compound. It suggests (and I think the authors sense this) that there are spaces (they refer to air content) in the pre-impregnated paper which are clear of impregnant. I feel that this point is shown up by the results in Table 6, where variation of the depth of butt spaces in the lapped insulation is seen to exert little or no effect on impulse strength. Fig. 6 also depicts a surprising relationship between impulse strength and gas pressure in the dielectric.

Based on experimental work which has led me to believe that increasing gas pressure raises the long-term a.c. breakdown strength of cable insulation but leaves the impulse characteristics relatively unaffected, I, too, formed an opinion many years ago similar to that expressed in Section 9.2 on the future development of dielectric materials. Stated briefly, the aim is to raise the impulse strength of cable paper insulation as high as is possible, and then to adjust gas pressure to suit any specified a.c. requirement.

I am always surprised at the disparity between the impulse strength of single paper and that of built-up insulation. Where and why does this loss of impulse strength occur? I find it hard to believe that most of it is caused by variation in paper uniformity. Another surprising fact is that there has been no appreciable improvement in this property since Davis published his 1 000 kV/cm figure in the *Journal* 16 years ago.* However, the authors do appear to be pointing the way to big improvements when they quote a figure of 1 600 kV/cm at 85° C achieved by incorporation of interleaved polystyrene in the insulation layers near the conductor.

Dr. Gazzana-Priaroggia (*Italy: read by* **Dr. F. J. Miranda**): I do not agree with the principle of applying statistical analysis only when investigating the relation between cause and effect between different variables. For instance, it seems hardly acceptable from a physical aspect to state in Section 4.3.1 that the effect of impermeability on impulse strength is 14·7% and that of density is 52·3%. Such a statement neglects entirely the physical aspect of the phenomenon and attaches unwarranted importance to an analysis of variance, which cannot take into account the possible presence of other variables between which no relation of cause and effect can be established. Thus, for instance, the analysis does not take into account the method of manufacture of the paper.

It is interesting to note that the authors have found a most marked decrease in impulse strength with temperature. Their findings are substantially in agreement with the results which I published in 1954.† Referring to Table 4, it would be interesting to know the thickness of insulation tested and the type of screen used. The tests recorded in Table 6 on the effect of paper thickness on impulse strength are of the same order as those obtained in my laboratory, but in many cases I found an increase in impulse strength with paper thickness. This may seem at first sight rather surprising, since the opposite happens in oil-filled dielectrics.

It is not clear whether all the sealing ends used on gas-filled cables are compound-filled or whether some are gas-filled. It would be interesting to know whether the breakdowns experienced in service on sealing ends have been associated with compound or gas filling. If the breakdowns are associated with compound filling, I wonder whether the stress cone shown in Fig. 10,

* DAVIS, R.: 'The Impulse Electric Strength of High-Voltage Cables', *Journal I.E.E.*, 1942, **89**, Part II, p. 52.

† GAZZANA-PRIAROGGIA, P.: 'Impulse Tests on High-Voltage Cables', *Elettrotecnica*, 1954, **41**, p. 289.

sharply cut a very short distance from the stress-control ring, was not the cause of internal electrical breakdown.

Mr. N. B. Hewett (*communicated*): The pre-impregnated dielectric is generally understood to be a non-draining type, and it was rather surprising to see a reference in Section 4.3.2 to the 'very low viscosity of the impregnant at 85° C'.

Furthermore, the use of a varnished Terylene tape in the joint dielectric, at the interface between the hand-applied paper and the tapered cable dielectric is the method used by the company with which I am associated for producing a barrier joint for 33 kV solid-type cables. There is something to be said on electrical grounds for retaining a semifluid impregnant for ordinary non-draining cables, but the reasons would not seem to apply to pressure cables.

The discussion of the effect of paper registration upon impulse strength is regrettably brief. Can the authors provide a more complete version of Fig. 4, extending from 10/90 to 90/10 registration? It must be assumed that, as the registration is increased beyond 75/25, the impulse strength will eventually begin to decrease, and it would be most interesting to know when this occurred. I have long felt that registration limits with a mean value near to 50/50, or even those which allow only a small variation from a given figure, are not necessarily the best limits if impulse strength, rather than surface tracking distance, is the main consideration. An impulse breakdown is normally radial, and the number of gap spaces in any radial line from conductor to core screen is the important factor. This number may well be at a minimum if the papers are applied with an even distribution or perhaps with a completely random distribution of registrations, and a statistical study of this matter would be valuable.

Previous studies* have always been based, I believe, upon the desirability of obtaining the maximum creepage distance along the paper surfaces, in order to minimize tracking in normal 50 c/s operation.

Mr. W. J. Nicholls (*communicated*): The method adopted by the authors (Fig. 1) of retaining the gas pressure by using a lead sheath reinforced with no less than four layers of metallic tape seems extraordinary when, by using a simple aluminium sheath, all other complications are eliminated. Perhaps the authors are more concerned with the restrictions on length involved with one method of aluminium sheathing, but there are others which do not so restrict the unjointed length of cable.

The desire for compacted or segmental conductors combined with the necessary compromise on dimensions, flexibility and conductivity (Section 9.1) may be fulfilled by taking advantage of the ductility of aluminium, which the authors agree is satisfactory as a conductor material and is frequently used nowadays. Further work in determining the correct tempers before and after forming to shape, and the degree of compacting, is undoubtedly required, but the results may well be rewarding.

Mr. I. P. Seth (*communicated*): The first sentence of Section 9.3 requires qualification, since up to, say, $0{\cdot}30\,\text{in}^2$ conductor size, the contribution to the total losses made by sheath and reinforcement is less than 10%. While the methods suggested for reducing sheath and reinforcement losses result in the virtual elimination of circulating-current losses in single-core cables, no similar application is available for 3-core cables; and with steel reinforcement, hysteresis losses alone can amount to some 15% of the conductor losses in large cables. Since the elimination of this effect by the use of tin-bronze as a reinforcing material is still rather costly, the development of non-metallic reinforcing materials will be watched with interest. If this investigation is carried further and non-metallic sheaths are introduced, the problems of earth faults and alternative return paths for earth-fault currents will have to be considered carefully. In addition, the elimination of sheath losses would be offset to a certain extent by the addition of a further thermal resistance in the heat-flow path.

In Section 13, it is interesting to note that a carbon-impregnated tape is applied over the rubber layer to act as an outer electrode during voltage tests on the serving. Normally, for cables laid in the ground, the graphite coating applied to the outer hessian tapes serves this purpose, but the graphite is omitted in cables having a fireproof finish. In some cases it is then impossible to carry out the standard C.E.G.B. 10 kV serving test. Where a carbon tape is applied, however, it is possible to test the servings in all circumstances. Cables installed indoors may be subjected to corrosive influences such as may occur in cable tunnels, and it is important that anti-corrosive servings are tested to ensure their soundness.

Mr. R. G. Torry (*at Manchester*): Is paper lapping still carried out on special machines, and, with the sizes of cables now being made, is there more than one pass through the lapping machine?

Routine tests are made at $30\,\text{lb/in}^2$ on the lead sheaths. For how long is this maintained, and at what stages in manufacture? Have all the lead sheaths to date been made on the single-ram vertical press or has continuous extrusion been used on either a double-ram or a screw-type press? Have the authors any comments to make on creep characteristics of the lead sheath?

Are any special precautions taken to avoid distortion of the rubber anti-corrosion sheath before it is vulcanized?

How does handling performance compare with other types of cable as regards dielectric and reinforcement? During transport and when in storage before laying, is the cable filled with air or nitrogen? Is the gas pressure slightly positive during this period, or might the pressure fall below atmospheric in a very cold climate?

Would the authors comment on the use of non-ferrous-metal accessories under gas pressure, and the possibilities of inter-crystalline fracture?

It is noted that there have been a few cases of failure of sealing-end porcelains under pneumatic pressure. Does this type of porcelain undergo temperature cycle tests only as a type test, and has consideration been given to applying these tests as routine in the light of these failures?

Mr. E. Kirkland (*at Manchester*): During 1957 three 33 kV gas-filled cable installations were undertaken in Manchester. The cables were not laid by contract, the order being for the supply and delivery only of cables and accessories. All the jointing was carried out by two Board jointers, who were given a short course on gas-pressure jointing technique in the manufacturers' works prior to the three installations being commenced.

The first two installations were successfully carried out, but the third presented some difficulty in that, although we were using joints of similar design to those already used on the first two installations, it was found impossible to gas the system, owing to leakages at joint positions. Eventually, new joints were produced, all joints on the installation were changed to this design and the feeder was successfully gassed. The main differences between the original joints and the joints now in service were the provision of locking and centralizing rings on the new joints, and a decrease in the diametrical clearances on the barrel application of the O-rings from $0{\cdot}02$ to $0{\cdot}01$ in.

The straight-through joint has been the subject of criticism, mainly because of the barrel application of the O-rings, and it has been suggested that a more certain gas seal could be made by the use of a double-flange type of joint. A great advantage of the existing joint is that, after the cast plumbs are made, the whole joint can be made gas-tight by drawing over the sleeve and bolting up the flange. Any other design should have this facility, and I

* Engineering Supplement to *Siemens Magazine* No. 197, October, 1941.

should like to know whether the authors are conducting investigations along these lines.

Mr. P. W. Cave (*at Manchester*): I was interested to note that after 22 months' storage the moisture content is only 0·23% and yet in the finished cable it is 0·38% or more. Presumably this additional moisture is picked up during subsequent manufacturing processes, but it does seem rather a lot when one remembers the extreme lengths to which other cable manufacturers go to ensure almost complete absence of moisture.

I was disappointed in the lack of test results on complete cable systems. Laboratory tests are all very well in their way, but it is the tests on the finished cable and its associated accessories which really matter, and we are only given the results of two tests and there is no indication as to the electric strength of the cable by itself. In the two tests quoted it was the joint which failed. In my opinion, a joint should be at least as strong electrically as the cable with which it is associated. If there must be a weak point in the system, it is better that this should be the sealing ends, which are more readily replaceable. In spite of these joint failures, Section 9.2 states that the electrical design has remained static, which is rather surprising.

In Section 4.4.3 there is the reference to the theoretical increase in maximum stress, based on the work of Levi Cevita; but surely he assumed a homogeneous dielectric, whereas the dielectric in this cable is certainly not homogeneous, consisting as it does of a combination of impregnated paper and gas spaces. It is therefore slightly misleading to compare the impulse strength of the screened conductor cable with the theoretical figures for a stranded conductor.

Mr. P. H. Leadbeater (*at Manchester*): There are one or two alterations and simplifications I should like to see made to the normal straight-through joint. First, for any through screen joint it is a great advantage to fit a flush ferrule. I realize that there would be difficulties in fitting this to an oval core, but a telescopic joint can be made. We have had no difficulty in training 33 kV jointers to make this type of joint, the circumference of which is very close to the virgin core. Any arguments against it on the grounds of mechanical strength are irrelevant, since every joint will pull out if some form of subsidence is present. I prefer the multiple stepped core to the long taper, because it is easier for the jointer to execute and goes a long way towards his avoiding what we refer to as a 'pappy' core and having to start taping all over again. Finally, I would insulate the joint throughout with impregnated-paper tape and abandon the various layers of Terylene tape introduced at the moment.

We have run into some trouble with O-ring seals in the normal straight joint, but the evidence to date is that this difficulty has been cured. It is unwise to make some radical change in design without full-scale field trials, for it is impossible to foresee all the ramifications.

In the 3-core-gas to three-singles solid terminating joint the gas-check pipe from the solid half of joint is taken from the top of a controlled-level filling orifice, and I am quite sure that, if it ever had to function, it would immediately be stopped up with bituminous compound. I consider it should be taken direct from the top of the expansion space and at the gland end of the sleeve.

In both the terminating joint and the sectionalizing, filling with bituminous compound negates the advantage of the O-ring seal, which is to be able to slip the sleeve on and off so easily. Hand-applied insulation could be taken over the condenser bushing and a through screen design developed and probably the overall diameter of sleeve reduced.

To freeze a cable for gas-leak location, liquid nitrogen is much safer than liquid oxygen and is satisfactory. It seems impossible to remove Arcton contamination from soil after a leakage, even after many months. We seem to need a second gas and detection apparatus which is selective to it.

On numerous occasions I have observed that the first paper from the conductor is contaminated with minute particles of copper, which do not became obvious unless the impregnating compound has been removed. This must surely have a detrimental effect on the breakdown strength of the cable by the production of stress points. If screening of the conductor is to be abandoned in later designs, I feel that it would be very desirable to ensure that this contamination does not occur.

The possibility of permanent reinforcing with glass fibre is very interesting, for I am convinced that the life of the dielectric is almost infinite and the life of the cable becomes the life of the reinforcement.

Mr. F. Mather (*at Manchester*): Section 4.5.3 suggests that trouble may be expected if the moisture content of the paper in a completed cable exceeds 0·6%. Can this be taken as a reasonable limiting figure for high-voltage paper-insulated cables in general?

Section 4.4.1 states that with a non-migratory impregnant and gas-filled butt gaps the onset of ionization will determine the ultimate a.c. performance. Is the same principle applicable to non-gas-filled cables with non-migratory impregnant?

Section 4.4.2 shows that under pressure conditions, doubling the conductor diameter lowers the impulse strength of the paper by 8%. Would this difference have been maintained if a greater number of impulse tests had been carried out?

Mr. C. R. Clarke (*at Sheffield*): Since the core papers pass over drying rollers at 200° C, is not the maximum permissible operating temperature of 85° C a little conservative? Many primary transformers in this area have paper insulation, but the first winding-temperature alarm is not given until after 85° C, and the transformer is not tripped out of service until 105° C is attained. Would the authors be worried if the core papers in one of their gas-filled cables reached 90° C?

The straight-through joint has a very convenient handle at the flanged end; fitted at the factory, it provides a convenient lifting or turning handle during its journey to the site and during installation. Should a pipe fracture or leak where it leaves the flange, the joint must be completely broken down, for it is too near the insulation to apply sufficient heat (this has occurred in this Sub-Area). Why not provide tapped holes ($\frac{1}{4}$ in gas thread) into which mechancial unions can be screwed? The external pipework would be fitted by the jointer on site and could be of any type or length.

The fitting for the gas pipe on the solid side of the terminating joint is useless. The filling plug should be as shown, but it is a mistake to let the fitting for the gas pipe reach down to the compound level. Any gas from the 'gas' side must come through the holes in the flange provided for the bushings. This creates a pressure within the compound and forces compound up the fitting into the pipe and renders the gauges inoperative.

Section 7.1 refers to the pulling-in loads applied to cables. The figure of 10 000 lb/in^2 is about half the breaking strain and allows a pull of approximately $5\frac{1}{2}$ tons on a 3-core 0·4 in^2 cable. Half this pull would be enough for me.

Can the authors give any advice as to minimum site handling temperatures?

The statement that 'the initial charging may be carried out progressively before jointing of the installation is complete' is misleading: charging can be carried out only on any one completed self-contained section, up to a sectionalizing joint, or the hand-applied papers could never be wound on over escaping gas.

The new halogen-gas detector is a very sensitive device but has its limitations—it is useless in wet weather. Has any research been carried out using sulphur hexafluoride? At 30 lb/in^2 this

gas has electrical characteristics equal to nitrogen at 200 lb/in^2. In detecting a gas leak it would be immediately picked up by the detector without the addition of a halogen 'carrier' gas to the nitrogen.

Dr. I. O. Butler (*at Sheffield*): The authors illustrate the very slow rate of increase in the mileage of gas-filled cable installed for all but the last few of the 20 years during which the system has been in commercial operation. Undoubtedly, the development by the manufacturers and its introduction to commercial operation by the users in the 1930's required considerable courage, owing to the revolutionary nature of the system. Is the very marked increase in the rate of acceptance within the last few years attributable to a late realization by the user of its merits, a late and pronounced improvement of its performance or some other cause?

Mr. R. G. Scotson (*at Newcastle upon Tyne*): In comparing the pre-impregnated and mass-impregnated pressure cables the significant differences lie in the type of compound used and the fact that the former needs no gas channel. There does not seem, therefore, the same risk of gas restriction due to compound movement as in the mass-impregnated type. I have long wondered why the pre-impregnated method of cable construction is not generally adopted, particularly when new plant is being installed, so avoiding the necessity for manufacturing special non-draining cables.

What is the permittivity of the paraffinic jelly and what is the change in capacitance following a heavy gas leak?

Until the advent of gas-filled cables, routine factory tests included over-voltage a.c. tests and power-factor testing from half to twice the working voltage to earth. For 66 kV the mass-impregnated cable has power-factor measurements taken at varying voltages up to working voltage to earth, i.e. 38 kV, but for the pre-impregnated cable the maximum voltage is 19 kV, which seems valueless. Power-factor testing of insulation at the lower voltages is of use only when it is intended to repeat the tests for comparative purposes. The value of the control exercised during impregnation and the power-factor testing of the impregnated paper becomes apparent when it is realized that no suitable testing is carried out on the completed cable in the factory.

What are the conditions imposed regarding pressure and voltage following a bending sample test, and how high is the direct voltage which is applied in place of the factory a.c. test at atmospheric pressure?

It is difficult to decide when a feeder should be switched out following a gas leak, particularly when the first indication is a low-pressure alarm at 1 500 lb/in^2 from the feed side.

Shortly after commissioning one of the first mass-impregnated cables in Northumberland, approximately 1 200 yd in length, a terminal pole at Bedlington became the target for some ·22 rifle practice and a single-core tail near the sealing bell at the remote end from the gas feed was hit; within 1½ hours the feed pressure was down to 20 lb/in^2 and the cable pressure to 5 lb/in^2. How would this pressure drop compare in pre-impregnated cable?

What is minimum pressure at which the cable could remain in service over a peak period of, say, 2–3 hours?

Why, in a long vertical drop at Kariba, is a hydraulic system preferred to a pneumatic one?

Messrs. E. P. G. Thornton and **D. H. Booth** (*in reply*): We shall reply to speakers in the order in which they took part in the discussions; where issues have been raised more than once we shall reply only to the person raising it initially. Owing to space limitation we can deal only with controversial issues.

Mr. Lane.—Since the Beaver and Davey paper four important design changes have been made, namely

(*a*) Oval conductors for 3-core 33 and 66 kV cables.
(*b*) Reduction of dielectric thicknesses.
(*c*) Substitution of the rubber anti-corrosion serving for second lead sheath.
(*d*) Simplification of accessory design.

The effect of these changes will obviously vary with conductor size and voltage, but their total contribution is about 35%. The advances in the engineering of a large single-core project by cross-bonding has resulted in additional savings of approximately 10%.

Mr. Barnes.—For cables with maximum stresses up to and including 90 kV/cm the use of a bituminous filling for the sealing ends is technically satisfactory and economic. When oil-polyisobutylene filling is used a reliable poultice is necessary, and our design has been proved by examination of sealing ends in service.

We have made an intensive study of the causes of reinforcement deformation, and the following summarizes our findings and the measures taken to prevent their recurrence:

(*a*) The lead sheath must be applied with a controlled degree of 'fit' so that the subsequent application of the reinforcement does not cause diametral collapse of the sheath and consequential slackness in the individual layers of tape.

(*b*) The individual layers of reinforcement must be applied with graded and carefully controlled tensions so that no layer of tape is applied with a tension greater than that used for the layer beneath. The direction of application of all the tape components of the reinforcement and serving must be arranged so that the torsional forces arising are reasonably balanced.

(*c*) When installing reinforced cables, care should be taken to avoid pulling-in techniques which give rise to excessive twisting. If the measures in (*a*) and (*b*) are observed the cable will be naturally resistant to twist, and experience shows that long lengths of such cable may be laid without risk of reinforcement deformation.

Mr. Sutton.—Varnished Terylene tapes are still used in certain accessories, since their application tightens the hand-applied paper dielectric and increases significantly the electric strength of the interphase between machine- and hand-applied dielectrics. Even under exaggerated test conditions, both with and without Terylene, we have not encountered disturbance of the hand-applied dielectric with loss of gas from the joint sleeve. Hollow conductors are used as a primary gas channel in submarine single-core cables because clearance-fit pressure sheaths are forbidden by the danger of collapse from external water pressure.

We feel strongly that the 10 kV d.c. serving test is most important in giving both manufacturer and customer complete confidence at the commissioning stage; and that there is every advantage in standardizing a common test voltage. Gas pressure will still be retained to maintain the a.c. electric strength when polystyrene is incorporated into the design.

Mr. Welch.—It is likely that a fillerless construction will follow our introduction of an aluminium-sheathed gas-filled cable, which will further reduce the cost.

We do not consider that the impregnating machines need be operated in an air-conditioned enclosure, since the outside sheets and end-cuts of an impregnated paper roll are always removed before the balance of the roll is slit into spools.

We have introduced additional process controls wherever failures in service have indicated their need, and where possible use automatic monitoring to ensure that the necessary standards have been achieved in any given process.

Mr. Hollingsworth.—To obtain a complete picture of the use of models for investigating the gas-filled cable dielectric we have presented information based on dielectrics having similar material characteristics. Paper densities lower than that now standard on the present highly stressed cable dielectrics were used for this series of tests—which explains the apparent discrepancy between the model (low-density) and cable (high-density) impulse-voltage results. The relationships established

in Section 4 have recently been reproduced on models having high-density dielectrics.

The modern thermal-resistivity figure of 550 is based on many experimental results and type tests in accordance with C.28, and its accuracy in relation to other types of cable tested in a similar manner must therefore be indisputable. The improvement from 750 to 550 is due to the use of different types of paper and a much harder dielectric achieved by higher lapping tensions. The permittivity is very largely governed by gap size, and the thermal resistivity by lapping tensions. We suspect that the relatively high thermal resistivity used for low-voltage mass-impregnated cables is due to the use of lower lapping tensions and to the difficulties associated with the measurement of thermal resistivity on thin-wall dielectrics.

We have been able to show only marginal improvements in impulse strength at high temperature by change of impregnant, and increased compound content may be an advantage, but this must not be gained at the expense of the present good pneumatic and non-draining characteristics.

We did not advocate aluminium sheathing until we were confident that the problems of anti-corrosion servings and accessory design had been resolved. The use of aluminium sheaths will also be advantageous economically if higher gas pressures are employed.

Dr. Arman.—Our work on the effect of repeated impulses on the gas-filled dielectric has yielded a similar order of reduction to that quoted in Reference 6 of the paper. In the loading-cycle test taken at 140° C the temperature was raised from 90° C in 10° C steps, thermal stability for at least six hours being achieved before any further increase in temperature was made.

Mr. Haddock.—We agree that the war-time finish applied to some of Mr. Haddock's 33 kV cables was not satisfactory, but we are confident that the modern anti-corrosion protection, the integrity of which is proved by factory and site tests, will be entirely satisfactory. We have recently been able to examine the rubber sheath removed from some 66 kV cables after six years' burial in bad soil conditions. The physical and electrical characteristics of this rubber are substantially unchanged from the virgin state.

Mr. Tellier.—We do not consider that the first gas-filled cable failed because of the high moisture content of the dielectric; moreover, the second, which is behaving satisfactorily, was not, in fact, manufactured in an air-conditioned atmosphere. Our own laboratory investigations have confirmed the advantages of sulphur hexofluoride in improving the a.c. performance of the dielectric.

Dr. Miranda.—The coefficient of variation of our model results is of the order of 7%. We have carried out many tests at full gas pressure and with mandrel temperatures of 90° C, and the relationships of Section 4 have been confirmed. The impulse strength at 90° C for 132 kV 1·0 in^2 cable is in the range 900–920 kV/cm, not 810 kV/cm as deduced by Dr. Miranda.

The test data on oil-filled cables are interesting, but one should take into account

(*a*) The necessity for near-perfect lapping and complete avoidance of creases for a 125 kV/cm dielectric with the essential requirement of installation without causing dielectric deformation.

(*b*) The increased charging power of highly stressed dielectrics and their effects on overall economics.

(*c*) Highly stressed gas-filled cables will be made possible by the use of the plastic films. This construction will have the added advantage that the stress on the impregnated paper is not increased above that now in use, and the charging power will not be proportionately increased.

Mr. Ball.—Our semi-flush ferrule is not of the design described by Davey, since the conductor is not hydraulically compressed before the ferrule is fitted. This new ferrule can be applied to compacted and/or shaped strands of equal or unequal cross-section. We have carried out extensive thermal tests on our unfilled joint sleeves and have no evidence of excessive ferrule temperatures under service conditions. However, under the exaggerated conditions of the test at 140° C, the failure in the joint was due to thermal instability.

Mr. Webb-Ware.—The maximum conductor stress of the gas-filled cable is controlled by its impulse performance under the standard C.E.G.B. impulse-voltage test for 33–132 kV cables of $4{\cdot}5\ (V + 10)$ kV. The nature of this formula ensures that, the lower the working voltage, the higher is the required impulse performance, and therefore the operating stress must be reduced accordingly. At 275 kV the specified impulse type test is lower than that required by the above formula, and hence with this critical voltage we have the highest conductor stress.

We agree the importance of unqualified stress is being over-emphasized and that more attention should be paid to mechanical handling. The recent introduction of bending tests on cables subsequently to be subjected to loading-cycle and impulse-type-approval tests is at least a step forward in this connection.

Mr. Orchard.—We consider that the high-voltage a.c. test at twice working voltage is restrictive of design and is not related to service conditions. The loading-cycle tests at one and a half times working voltage, together with the thermal-stability test at 132 kV and above, provide adequate evidence of the a.c. factor of safety. There are ample data to support the view that, for a gas-filled cable, unless the ionization-inception voltage is considerably overstepped, there will be no a.c. deterioration within the dielectric.

Dr. Salvage.—The formula given in Section 4.3.1 was derived from test data on sheet paper at ambient temperature, and is a most useful guide when comparing the anticipated performance of different papers. It is true that in an earlier discussion one of us stated that density was of less importance than impermeability in the gas-filled dielectric, but since then we have studied the impulse performance over a wider range of paper densities and have now found that, at both ambient and high temperatures, density is of primary importance. For a sheet-paper test at ambient temperature on a high-density paper, figures of 2·2–2·4 MV/cm are obtained. On the cable this is equivalent to 1·14–1·24 MV/cm at ambient temperature and 900·980 kV/cm at 90° C.

Mr. Mitchell.—The comments on the cable installed in the Mersey Tunnel confirm that the cable has a reduced fire hazard and can be rerouted without affecting the dielectric and reinforcement.

Mr. Johnson.—It is dangerous to compare the a.c. stress limit of gas- and oil-filled cables, since on the former the controlling factor is the ionization-inception voltage, which is easily ascertainable. In oil-filled cables, however, a long-term deterioration of the oil may well occur at high stresses, and this is not so easily discerned by short-time testing. We have carried out a large number of degassing cycles on typical gas-filled cables systems and have not detected any change in the a.c. ionization-inception stress or impulse strength.

Mr. Morgan.—The 180 lb/in^2 quoted in the Appendix is the continuous minimum operating pressure of the system, whereas the 125 lb/in^2 quoted in Section 5.3 is the minimum under emergency conditions. At 125 lb/in^2, reference to Fig. 6 shows that, even with 4-mil papers, on cables operating at a conductor stress of 100 kV/cm, ionization inception did not occur until well above working voltage. We see no difficulty in obtaining pressure porcelains having a test withstand sufficiently in excess of 600 lb/in^2 to allow the use of a nominal operating pressure of 300 lb/in^2. It is almost certain that the mechanical failures of certain pressure porcelains were due to defects in the manu-

facture of the porcelains themselves. Elaborate tests have failed to show that the failures, which were of a tensile nature, were related in any way to the design, the method of compound filling or to expansion and contraction effects during loading cycles in service.

Mr. Gosling.—We agree that careful attention to methods of installation and site costs can often yield far greater economies than increases in conductor stress and is, in fact, a far better approach to the problem of economic system design. Unfortunately, the introduction of the hollow-conductor design would increase the first cost of the cable, and in any case it is pertinent to emphasize that, when regassing cables of present design, very rapid gassing rates can and have been used.

Mr. Raine.—The dessicant used is anhydrous methanol with an initial moisture content of 0·005%.

Mr. Hawley.—The difference between the impulse strength of a single-paper and a built-up insulation is due to the presence of the butt gaps in the latter. The effect of these butt gaps and the way in which they are arranged is shown in Fig. 4, in which we give data on the variation of impulse strength with paper registration.

Dr. Gazzana-Priaroggia.—The formula given in Section 4.3.1, although originally based on statistical analysis of a comparatively small number of test results, has since been substantiated by our later tests. In obtaining the test data given in Table 4, models having an insulation thickness of approximately 0·020 in were used and the conductors were plain mandrels. The outer screening was of overlapped tinfoil. All sealing ends used on the gas-filled system are compound filled. No breakdowns have been experienced in service on sealing ends having the type of stress cone shown in Fig. 10.

Mr. Hewett.—As emphasized in Section 3, the non-draining nature of the dielectric is obtained by control of surface compound by means of the scraping process and not by the use of a high-melting-point impregnant. The non-draining characteristics have been proved by very many drainage tests at temperatures in excess of the maximum operating temperature of the cable. The data given in Fig. 4 for the variation of impulse strength with registration cover the range of registration in common use, and it is obviously clear that discontinuities will occur when the registration approaches the condition of riding papers.

Mr. Nicholls.—We agree that the decrease of conductivity with work-hardening on compacted conductors will be less with aluminium than with copper.

Mr. Seth.—Even with small conductor sizes, once single-point or cross-bonded techniques are used it is permissible to lay cables spaced at flat formation, with consequent improvement in current rating due to the improved heat-dissipation characteristics.

Mr. Torry.—Paper lapping is not carried out on special machines, but modern paper lappers are now capable of applying all the papers in one pass for 132 kV cables. The routine gas-tightness test at 30 lb/in^2 is carried out over a period of 48 hours and is now done only in the finished stage. During transport and when in storage before laying, the cable is filled with nitrogen at a slight positive pressure. The pressure porcelains undergo temperature-cycle treatment only as a type test, and it is considered dangerous by some authorities to extend the use of these tests as a routine on every porcelain.

Mr. Kirkland.—We are satisfied that the troubles which occurred on the original design of joints, employing barrel application of O-rings, have been completely overcome. We have now redesigned the barrel seal, and the new construction offers increased robustness and simplicity.

Mr. Cave.—In considering the earlier designs of gas-filled joint we believed that greater advantage could be had by simplifying the mechanical rather than the electrical design.

Mr. Leadbeater.—We do not agree that the married ferrule has any real advantages, and believe that our own design provides the best combination of freedom from electric-field distortion, mechanical strength and speed of application. With the present design of condenser bushings it is impossible to tape satisfactorily over their surfaces, and thus it is impossible to dispense with bitumen or oil filling. We feel that the Arcton concentration problem has been alleviated in recent months by the use of a modern detector which has a variable sensitivity control.

Mr. Mather.—The data on the effect of moisture on electrical characteristics given in Section 4.5.3 are applicable only to the gas-filled dielectric. Although changes in electrical characteristics are shown to occur with moisture contents in excess of 0·6%, this does not mean that trouble would necessarily be expected in service from a cable having a moisture content of this order. With the high stress level associated with pressure-assisted cables, the a.c. performance will be controlled by the onset of ionization. With solid-type cables, however, operating at lower stresses, this is not necessarily so, since the energy associated with ionization is of a low order.

Mr. Clarke.—We imagine that there must be many cases where gas-filled cables have been called upon to operate at temperatures in excess of 85° C, and we are not unduly concerned about this from the aspect of the dielectric. It should be realized, however, that the maximum operating temperature of any cable is controlled partly by electrical and partly by mechanical considerations. If cables are operated considerably above their maximum temperature for long periods, the life of the cable may be shortened. For cables manufactured for use in this country we do not recommend installation at temperatures lower than 0° C.

We do not attempt to joint a cable length during gassing. Progressive gassing is used on a long installation, and the route is divided into a number of sections, each of which may be proved pneumatically and straight-jointed to the next section.

Dr. Butler.—The increase in rate of usage in the post-war years is due to the increase in demand for pressure-assisted cables.

Mr. Scotson.—The paraffinic jelly has a permittivity of 2·2 and there is no change in capacitance following a heavy leak.

The measurement of base dielectric power-factor gives a good routine control of manufacture, but we agree that, fundamentally, the best detailed control is given by rigorous testing of the raw materials. The minimum direct voltage applied in the routine test and after bending is twice the system voltage.

With the gas-filled cable there is no need to switch a cable out of circuit until the terminal pressure falls below 125 lb/in^2. For a serious gas leak the rate of loss of gas for a gas-filled cable would be very much lower than that applying to a mass-impregnated pressure cable. This is due to three characteristics of the gas-filled cable, namely its higher total gas volume, its high pneumatic resistance and its use of the strand as a primary gas channel.

621.317.331: 55

The Institution of Electrical Engineers
Paper No. 2791 M
Dec. 1958

EXAMPLES OF GEOELECTRIC SURVEYS

By Professor L. S. PALMER, D.Sc., Ph.D., F.Inst.P., Member.

(*The paper was first received* 14*th January, and in revised form* 3rd *October*, 1958. *It was published in December*, 1958, *and was read before the* SOUTHERN CENTRE 28*th January, and the* MEASUREMENT AND CONTROL SECTION 3*rd February*, 1959.)

SUMMARY

The Introduction deals briefly with the general principles underlying geoelectric methods of surveying and gives a simple formula for the apparent resistivity at a given depth below the surface in a homogeneous medium. The two problems of interpreting the different kinds of curves obtained from field measurements and of determining the depth of the associated geological anomalies are discussed.

In Section 1.2 the electrical equipment and field procedure are briefly described.

Three particular anomalies are considered in Section 1.3. These are:

(i) Parallel strata as illustrated by the boulder-clays which overlie the chalk of the Holderness Plain, East Yorkshire.

(ii) Inclined strata which occur where the water-table reaches the surface on the slopes of the Mendip Hills, Somerset.

(iii) A cavern in the limestone rocks at Pen Park near Filton, Bristol.

In Sections 2, 3 and 4 respectively, the relevant equations, the geoelectric measurements and graphs together with their interpretations are discussed. The equation for inclined strata is deduced in a form comparable with the previously published equations for parallel strata and a spherical cavity. These latter are stated in Sections 2 and 4 respectively, and their derivation is given in the Appendix.

From the graphs in Section 2 it is concluded that no ancient Humber estuary existed in the chalk beneath the boulder-clays, but the presence of an interglacial gravel separating two deposits of boulder-clays is established.

In Section 3 the water-table is located and is found to emerge along a line of springs which coincides with the edge of the conglomerate deposited by the ancient Triassic sea.

The deductions made from the graphs of Section 4 were verified by subsequent excavations which led to the rediscovery of Pen Park Hole.

In the Appendix the derivation of the equations for a homogeneous medium, for parallel strata and for a buried sphere are given, together with theoretical relationships for calculating the depths of these particular anomalies.

LIST OF SYMBOLS

a = Half the distance between the current electrodes, ft.
a_0 = A critical value of a.
b = Half the distance between the potential electrodes, ft.
d = Distance, ft.
h = Depth below surface or boundary, ft.
I = Current, amp.
$k = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ = Reflection coefficient of the boundary between two media 1 and 2.
n = An integer.
n_e = Number of effective images formed by inclined mirrors.
r = Radius of a circle of images or of a spherical cavity, ft.
R = Measured resistance, ohms.
V_P = Potential at a point P, volts.
$\alpha = b/a < 1$.
$\beta = h/a = (r \sin \theta)/a$.
ρ_0 = Resistivity of air $= \infty$.
ρ_s = Apparent resistivity at a depth h, ohm-ft.
ρ_x = Resistivity of medium x, ohm-ft.
θ = Angle between inclined strata.

Prof. Palmer is Professor Emeritus in the University of Hull and Honorary Curator, Wells Museum.

(1) INTRODUCTION

(1.1) General Principles

It is over forty years ago that Wenner[1] first published his particular technique for geoelectric surveying. His method is occasionally employed to-day[2] where the circumstances are thought to be suitable. Since that time (1916) many modifications have been suggested but the general underlying principles are the same. Briefly, an electric current is sent into the earth through two electrodes C_1 and C_2 inserted in the surface to a depth of a few inches. The earth with the two current electrodes constitutes a form of three-dimensional potentiometer over the surface of which is a potential 'pattern'. This pattern depends on the current distribution, which in turn depends on the variations of the electrical resistivity throughout the half-space bounded by the earth's surface and extending downwards to infinity, the upper half-space being air of infinite resistivity.

The potential fall between any two points on the surface can be measured by the insertion of two additional probes or potential electrodes P_1 and P_2 at the points between which the potential fall is to be measured. The ratio of the measured potential difference to the current flowing is a function of some 'mean' and localized value of the earth's electrical resistivity.

This 'mean' value will depend on the variations of the electrical properties of those portions of the earth's crust through which the major part of the current passes; whilst the electrode configuration on the surface will determine the location of the particular region, the mean resistivity of which can be calculated from the potential/current ratio, or 'potential function' as it is usually termed.

The name 'apparent resistivity' is used to distinguish this 'mean' value from the normal resistivity that would be determined by laboratory measurements on different samples of the rocks comprising the earth's crust.

Of the many suggested electrode configurations, some involve variable electrode spacings with or without one or more electrodes fixed in position throughout a set of measurements. Often when the field technique is simple and quick to use, the computations are the more tedious and complicated. Whatever method is used, the objective is to obtain a set of apparent resistivity measurements at different depths below the point on the surface (the station) in the neighbourhood of which the electrodes are situated.

With the original Wenner method, the four electrodes were equally spaced along a straight line bisected by the station, so that $C_1P_1 = P_1P_2 = P_2C_2 = d$. The apparent resistivity at a region immediately below the station is then given by

$$\rho_s = 2\pi dR \text{ ohm-ft} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where d is measured in feet and R is the ratio of the measured potential fall in volts to the circulating current in amperes.

It will be obvious that the depth below the station of the region of apparent resistivity ρ_s will increase with increase in the spread of the current electrodes. This follows because the current will penetrate more effectively to a greater depth when the distance C_1C_2 is large. It has been customary with the

Wenner technique to assume that the depth of this region to which ρ_s refers is equal approximately to half the distance C_1C_2.

The method used throughout the surveys described below is a generalized form of the Wenner method, in which the four electrodes are aligned symmetrically about the station, but, instead of being equidistant, the ratio P_1P_2/C_1C_2 is kept constant throughout any given series of observations. The apparent resistivity below the station is then given by [see Appendix 7.1]

$$\rho_s = \frac{\pi(1-\alpha^2)}{2\alpha} aR \text{ ohm-ft} \quad . \quad . \quad . \quad (2)$$

where α is the ratio P_1P_2/C_1C_2 and is less than unity, a is $C_1C_2/2$ft and R is the ratio in ohms of input voltage to output current.

If α is made equal to $\frac{1}{3}$, eqn. (2) reduces to eqn. (1) for the Wenner technique. The ability to choose different values of α for different sets of readings makes the present method very flexible. This is useful in the field because the larger the value of α, the greater is the measured potential. Consequently the same instrument can be used with equal accuracy on low-resistance wet peat or on high-resistance dry limestone. Furthermore, with large values of α, Huber[3] has shown that variations of measured resistivities due to surface irregularities are reduced to a minimum.

It is convenient to plot values of a as ordinates against values of ρ_s as abscissae calculated from eqn. (2). By plotting in the second quadrant (i.e. a minus), the ordinates read downwards as functions of the depths and the abscissae increase to the right with the usual system of Cartesian co-ordinates.

Thus, when the station is situated above a homogeneous medium, i.e. one with uniform resistivity, the resulting graph will be a straight line parallel to the ordinate axis and intercepting the axis of abscissae at a value of ρ_s depending on the electrical nature of the rocks beneath the station. The equation of this graph is $\rho_s =$ (a constant) for all depths.

Variations or anomalies in the resistivity of the ground below the station, such as are produced by changes in geological structure, or by the presence of water, metal ore deposits, air cavities, etc., will produce more or less complicated curves from which the type of anomaly and its depth are to be determined.

Thus the two major theoretical problems in geoelectric surveying are:

(i) To associate particular types of curves with given geological anomalies.

(ii) To relate the ordinate values of the points of inflection or changes in slope with the actual depth below the surface at which the associated geological anomaly occurs.

The first problem can be studied from families of curves of the appropriate potential function, and the second problem entails the solutions of the second and first differentials respectively of the appropriate potential function.

For many years empirical rules were employed, based largely upon experience in the field. Examples of such rules are the Gish–Rooney law and the Peak rule.[4]

With the three particular anomalies dealt with in the following Sections, attempts have been made (see Appendix) to determine the theoretical relationships between the ordinate values of changes in the graphs and the depths of the associated anomalies below the surface of the earth. In many cases it has been possible to compare conclusions arising from these relationships with bore-hole data or with measurements based upon subsequent excavations.

(1.2) Apparatus

Because of serious interference from earth currents and contact potentials, a simple battery-operated circuit connected across the current electrodes and a voltmeter connected across the potential electrodes will not give reliable results. Furthermore, it would be convenient to make observations directly in ohms. Obviously from eqn. (2), a voltmeter could be calibrated in ohms if the current were kept constant. This is possible with suitable current controls. Methods must also be devised to inhibit the effects of earth currents and contact potentials where the electrodes are inserted in the ground.

The type of circuit finally adopted for the work described in this paper is shown in Fig. 1. A manually-operated direct-current generator passes a current from winding N_1 to the earth through the current electrodes C_1 and C_2. The current is registered by the ammeter A and kept constant by adjusting the resistor R. S_1 and S_2 are mechanically-operated low-frequency reversing switches. The resulting low-frequency potential generated between P_1 and P_2 is mechanically commutated by switches S_3 and S_4, with the result that a direct current passes through the galvanometer G_1. This circuit is protected by condensers as shown, from direct earth currents and from potentials set up at the electrode-earth contacts. Another direct current from winding N_2 of the generator passes through the potentiometer P in such a direction that it is opposed by the direct current coming from the potential electrodes. By adjusting the slider of the potentiometer, the galvanometer G_1 can be used as a null-recording instrument. The back-current from the generator necessary to do this is passed through the deflecting coil D of the galvanometer G_2, the controlling field of which is provided by the constant current I in the coil C. Thus, the deflection of the needle will be proportional to the current through D, i.e. to the potential generated across P_1P_2. Since I is kept constant, this deflection can be calibrated directly in ohms, and the galvanometer G_2 thus functions as an ohmmeter.

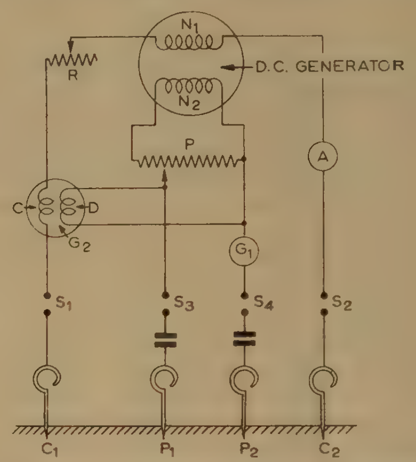


Fig. 1.—Circuit diagram of electrical equipment.

The adoption of low-frequency reversing and commutating switches, which are controlled by the revolutions of the manually-operated handle of the generator, overcomes the troubles due to earth currents and contact potentials without introducing the reactance and phase difficulties associated with a.c. bridge methods.

For simplicity, the various shunt and series resistances introduced to extend the ranges of the instruments have been omitted from the diagram.

Concerning the electrodes, for most top-soils $\frac{1}{2}$ in diameter steel rods are suitable. One end is pointed and preferably case-hardened, and the upper end is looped round to form a convenient handle. The overall length can be about a foot. Such electrodes can be pushed into the ground by hand. It is convenient to connect the cable by inserting the end of the wire into a hole

drilled through the electrode, the wire being secured by a grub-screw.

For hard rock it is necessary to drive electrodes in with a small sledge hammer. Suitable electrodes for this purpose can be made from 1½ in diameter steel tubes, the lower ends of which are plugged and welded with case-hardened steel points. A steel driving bar, which fits loosely into the tubular electrode and protrudes several inches above it, is used for driving the electrode into the rock. With this design, the top of the electrode is undamaged whilst the burring over of the top of the driving bar does not matter. The cables are conveniently fastened to small iron collars which slip over the electrodes and are secured by grub-screws. For removing these electrodes, tommy-bars can be inserted through holes drilled at the top of the tubes. The overall length of the electrodes need not exceed 15 in.

Four heavy t.r.s. cables wound on suitable drums, and measuring tapes, complete the essential field equipment.

With the technique adopted in the work here described, all four electrodes need to be moved for each measurement. For this operation it is convenient to employ four people. A minimum of two others is necessary to operate the station: one adjusts the potentiometer and records the ohmmeter readings, and the other operates the generator and signals to those moving the electrodes.

To facilitate the calculation of ρ_s from eqn. (2), a slide-rule has been designed from which this quantity can be read directly with only one adjustment of the slide. This has been of considerable value in the field when graphs need to be plotted and interpreted before more stations can be sited. The design of the slide-rule depends on the fact that α in eqn. (2) is kept constant for a given series of readings. Eqn. (2) can be written in the form

$$\frac{\rho_s}{R} = \frac{a}{f(\alpha)} \text{ where } f(\alpha) = \frac{2\alpha}{\pi(1-\alpha^2)}$$

It is now apparent that an ordinary slide-rule with the fixed scale appropriately marked with values of $f(\alpha)$ can be used to read off values of ρ_s against recorded values of R. The necessary adjustment is to move the slide so that a given value of a coincides with the particular value of $f(\alpha)$ in use. The value of ρ_s on the slide then coincides with the particular value of R on the fixed scale, a and R being corresponding field readings.

(1.3) Anomalies

The three anomalies discussed below are:

(i) Parallel strata of different thicknesses and resistivities: in particular the boulder-clays of the Holderness Plain, East Yorkshire, which overlie the chalk and are overlain by top-soil. A thin gravel seam usually separates the two different boulder-clays, which were deposited during successive glacial climatic phases.

(ii) A water-table marked by a line of springs rising on the side of a steep hill: in particular the water-table at Link Batch near Burrington Combe on the Mendip Hills, North Somerset, where the upper dry limestone overlies a wet limestone and results in a series of springs debouching along the north side of the hill.

(iii) A cavern containing water: in particular the cavern known as Pen Park Hole near Filton, Bristol. The cavern is situated in limestone which is covered by a layer of clay. A lake lies in the bottom of the main chamber, which has several passages and tunnels connected to it.

(2) HOLDERNESS BOULDER-CLAYS

Geoelectric measurements were made across the Holderness Plain, East Yorkshire, during the post-war years and were completed in 1954.

(2.1) Objectives

It has been suggested that the River Humber once flowed into the North Sea by way of a wide estuary situated south of Skipsea some 20 miles north of the present river mouth. To test this hypothesis was one of the objectives of the survey. It was proposed to measure the depth of the low-resistance boulder-clays and thereby to plot the contours of the underlying relatively high-resistance chalk.

Additional objectives were to determine the position and continuity of the interglacial gravels which were believed (from bore-hole observations) to separate the upper and lower boulder-clays. It was also thought that the distribution and depth of the boulder-clays would yield information concerning their deposition and also lead to further knowledge about the lateral and terminal moraines with which they are associated.

(2.2) Theory

The theory of resistivity measurements in localities below which lie parallel strata of different thicknesses and resistivities has been published by many authorities.[5–8] The general formula for the apparent resistivity ρ_s at different depths in a two-layer system is (using the above nomenclature)

$$\rho_s = \rho_1\left[1 + \frac{(1-\alpha^2)}{\alpha}\sum_{n=1}^{n=\infty} k^n\left\{[1-\alpha)^2 + (2n\beta)^2]^{-1/2} - [(1+\alpha)^2 + (2n\beta)^2]^{-1/2}\right\}\right] \quad (3)$$

where ρ_1 is the resistivity of the top layer of thickness h, ρ_2 is the resistivity of the lower layer of infinite thickness, β is the ratio h/a and $k = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ is usually known as the reflection coefficient from its obvious analogy with the optical case (see Appendix 7.2).

Typical graphs for two and three layers are given by most authors, and the particular relationship between points of inflection on the graphs and the depths of the boundaries between adjacent layers has been determined by Palmer and Hough (Reference 4, Fig. 2). With this knowledge it is possible to calculate the depths of the several boundaries in a multi-layer system.

(2.3) Technique and Survey

The depth to which measurements can be taken depends on the extreme distance between the current electrodes and corresponds very roughly to half this distance. As the current electrodes are brought nearer and nearer to the station, so the potential electrodes are moved to such positions that α is kept constant and always less than unity. For low-resistance boulder-clays it was convenient, with the instruments available, to make α equal to 0·7 or 0·8.

Readings were usually taken for values of a from 5 to 380 ft, at which latter distance the effects of the chalk on the shape of the graphs were fully apparent. Graphs were then plotted with the values of ρ_s calculated from eqn. (2) as abscissae and with the distances a as ordinates.

Fig. 2 shows four lines running approximately north–south along which 44 stations were sited. At most of these stations two traverses were laid out, one parallel to the line of stations and one perpendicular to it. The use of two mutually perpendicular traverses served as a check on the measurements and confirmed any minor anomalies arising from the occurrence of any unsuspected stratum (such as a layer of low-resistance peat or a seam of high-resistance sand or gravel) in what was assumed to be a uniform deposit of boulder-clay of constant resistivity.

(2.4) Results

Apart from local variations depending on the depth of the chalk, the graphs for 30 of the stations (for example, B13) are three-layer types that might be expected from the known geological structure of the Holderness Plain. In most of these three-layer graphs the minimum value of ρ_s is not less than 100 ohm-ft.

Of the remaining 14 stations, a group of 7 stations (enclosed in circles in Fig. 2) lie on a roughly semicircular or horse-shoe-

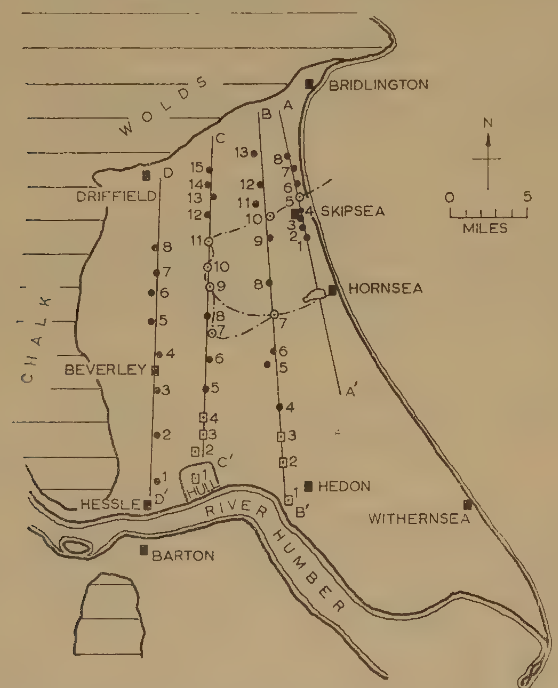


Fig. 2.—Distribution of stations on the Holderness Plain.

shaped line running from Ulrome westwards through Beeford and North Fordingham, thence southwards towards Burshill and possibly as far south as Routh before turning back eastwards through Sigglesthorne towards Hornsea. The graphs for these stations (for example, B10) conform more closely with two-layer graphs than with the three-layer types. Their straight portion conforms roughly with the equation $\rho_s \simeq 100$.

The remaining 7 stations (enclosed in squares in Fig. 2) are all situated immediately north and east of Hull and in Hull itself. The graphs (for example, B2) are characterized by very low minimum values of ρ_s, usually less than 30 ohm-ft.

It is not possible in this paper to reproduce the graphs for the 44 stations. The graphs for three stations on the line BB′, however, are shown in Fig. 3. These have been selected as typical of the three types mentioned above. Furthermore, in the locality of each of these stations was a bore-hole, the geological section of which could be compared with deductions made from the respective graphs. These sections, which are shown in Fig. 3, have been compiled from the Geological Survey Memoir on 'Holderness' and from Wartime Pamphlet No. 12 on 'The Water Supply from Underground Sources in East Riding and North Lincolnshire', by K. P. Oakley and others. By selecting stations all on the same line (BB′) it is possible to see how the interpretation of their graphs has contributed points on the N–S section along BB′ which is drawn in Fig. 4.

(2.5) Interpretations

The geological significance of this geoelectric survey will now

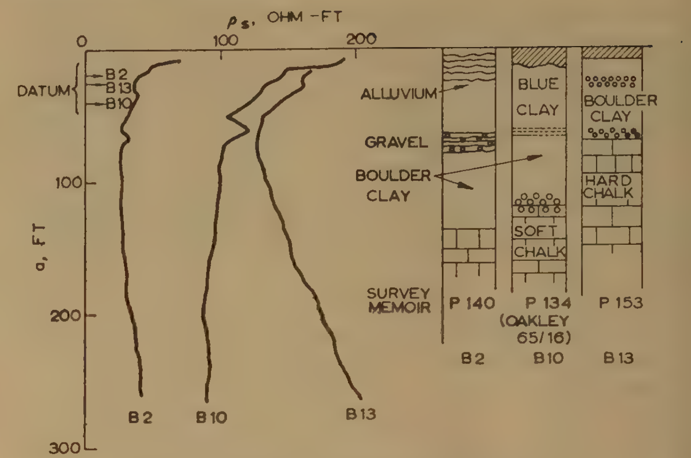


Fig. 3.—Graphs for stations B2, B10 and B13.

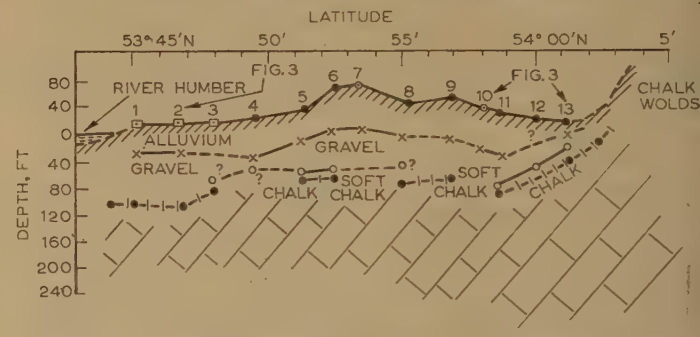


Fig. 4.—S–N Section along BB′ from geoelectric measurements.

×—×— Gravel. } Geoelectrical.
○—○— Chalk.
|●—|—● Chalk. Bore-holes.

be indicated. Comparisons with the bore-hole data will then show to what extent a survey of this kind can be of practical use to engineers and geologists.

In order to calculate the depth of the chalk or the thickness of the total overburden it is necessary to determine for the appropriate value of k the value of $\beta(=h/a)$ for the particular ratio of $\alpha(=b/a)$ in use. Then the product βa_0 (where a_0 is the value of a for the lower point of inflection of a three-layer graph) gives the required depth h. Details of this procedure are given in Reference 4.

There are two general conclusions which follow when the 30 three-layer graphs are considered as a whole. The first concerns the depth of the boulder-clay. Along the line BB′ these glacial clays are roughly 100 ft deep, along CC′ they are about 40 ft and they thin out to 20 ft along the line DD′. They also become very shallow as they approach the chalk wolds towards the north. There does not seem to be any evidence for a large pre-glacial estuary in the chalk as was once surmised.

The second general conclusion concerns the small high-resistance kinks which appear in many of the graphs. They occur for values of a equal to about 60 ft along the line BB′, and 20–30 ft on line CC′, but could not be distinguished on the graphs for any of the stations along DD′. The interpretation of these kinks is assisted by a knowledge of the bore-hole and coastal sections. Frequently at depths corresponding to these values of a, strata of sand or thin gravel seams occur, and are considered to be evidence of an interglacial phase which marked the interval of time between the deposition of the lower and upper boulder-clays.[9, 10] Thus these kinks appear to be geoelectric evidence for this particular interglacial period.

The two-layer graphs, such as B10 in Fig. 3, indicate that

deposits of very low resistivity occur below these stations. With some knowledge of the local geology it is reasonable to suppose that these low-resistance deposits arise from either abnormally wet clays or from soft wet broken chalk. Soft chalk has been recorded at several of these stations, and it is thought that the graphs are due to wet chalk rather than to wet clay. The so-called 'Beeford Clays' may be an exception to this. The distribution of these particular stations (see Fig. 2) coincides with the horse-shoe-shaped peripheral edges of a tongue of boulder-clay which is surrounded with terminal and lateral morainic gravels.[11]

That these two-layer graphs appear to extend to indefinite depths is due to the fact that any wet low-resistance deposit acts as an electric screen effectively preventing the penetration of the current to lower formations. This is particularly noticeable with subterranean lakes in limestone caves, where the graphs appear to suggest an indefinite depth of water, even though the lake might be very shallow (see Section 4). Water-logged deposits are consequently effective barriers against deeper geoelectric measurements. Thus these two-layer graphs indicate the position of wet broken chalk, and, together with the superficial morainic gravels, mark the western advance of the particular tongue of boulder-clay with which they are associated.

The geological explanation of the seven remaining graphs lies in the fact that all the stations are situated on the very low-resistance alluvial deposits which mark the older courses of the Hull–Humber river system.

These examples are illustrative of the simple two- and three-layer types of graphs which arise from a number of superimposed parallel strata. Graphs somewhat similar to the above have recently been obtained by Habberjam and Whetton on the boulder-clays in Co. Durham.[12]

(3) MENDIP WATER-TABLE

The measurements described in this Section were made during the summer of 1948 in order to test the theory which had been developed in the spring of that year.

(3.1) General Problem

This work was undertaken as an example of the application of geoelectric methods to the problem of inclined strata. It was known that the resistivities of wet and dry limestone were sufficiently different for the boundary water-table to be treated as the boundary between two geologically different strata. Consequently, where a water-table comes to the surface—a location usually marked by a line of springs—there will be an intersection between two inclined boundary planes. This situation is illustrated in the diagrammatic section depicted in Fig. 5.

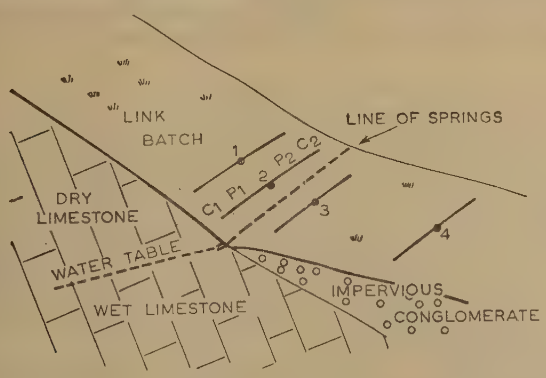


Fig. 5.—Diagrammatic section through Link Batch, Mendip Hills showing the four stations.

A water-table is not necessarily horizontal.* It often rises towards the surface, and, with the site chosen, the surface itself was also inclined to the horizontal. We thus have a situation appropriate for testing the theory underlying the problem of inclined strata.

(3.2) The Site

The foregoing conditions arise on the north and south sides of the Mendip Hills, where, towards the foot of the hills, there is a line of springs. These springs occur where impervious Triassic conglomerate rocks overlie the mountain limestone. Below the line of springs the limestone is wet, and above that line it is relatively dry.

A site was chosen on the north face of the Mendips near the bottom of Burrington Combe. Here, at Link Batch, open fields enable traverses to be sited without obstruction by vegetation. Four traverses were selected, as shown in Figs. 5 and 6, and

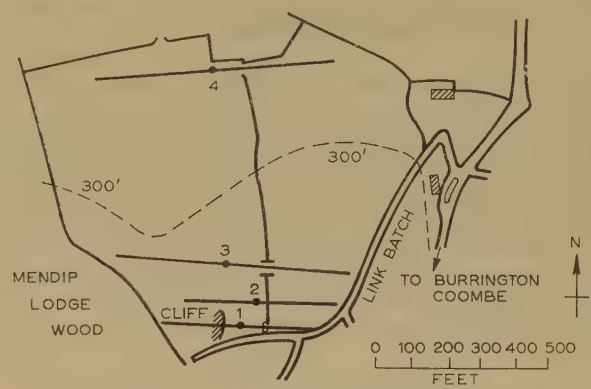


Fig. 6.—Plan of Link Batch traverses.

were chosen so that stations 1 and 2 were above the dry/wet limestone boundary and the lower stations 3 and 4 were on the conglomerate.

(3.3) Theory

It is proposed to give in this Section a brief outline of the theory concerned, based on the method of electric images. This was first attempted by R. F. Aldredge.[13] Later Miss Skalskaya,[14] M. Unz,[15] Katsuro Maeda[16] and J. C. de Gery, with G. Kunetz,[17] derived more rigorous solutions involving Bessel and similar functions.

The theory of inclined strata involves the problem of the effective number of multiple images produced between two plane mirrors inclined at any angle. Consider station 2 in Fig. 5. The simplified equivalent problem using Maxwell's theory of electric images is indicated in Fig. 7, in which, for convenience, the hillside is shown horizontal. The circles are the loci of the electric images arising from the equivalent current source and sink of $+2I$ and $-2I$ at C_1 and C_2 respectively. P_1 and P_2 are positions of the potential electrodes. ρ_0, ρ_1 and ρ_2 are the resistivities of air, dry limestone and wet limestone respectively, ρ_1 being greater than ρ_2. Because of these resistivity values, the two 'mirrors' will have different reflection coefficients; that of the dry-limestone/air boundary is $(\rho_0 - \rho_1)/(\rho_0 + \rho_1)$ and is equal to $+1$ because ρ_0 is equal to infinity. This mirror is therefore opaque, with a back coefficient of -1. The reflection coefficient of the water-table will be $-k$ and equal to $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$. This mirror is therefore semi-transparent

* When water falls on a hill it may sink as vadose water to a level appreciably below that of the phreatic water which emerges along the sides of the hill. The surface of the water-table is consequently not necessarily a horizontal plane, but is often saucer-like. The curved surface of water confined within the solid rock should not be confused with the horizontal surface of the free water in an open pond.

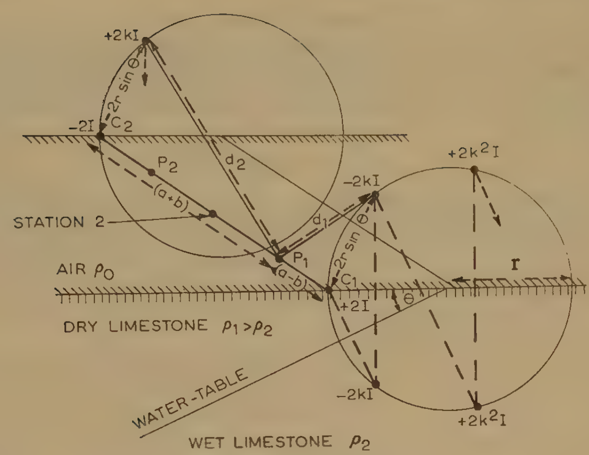


Fig. 7.—Diagram of inclined strata with traverse C_1C_2 and associated electric image circles.

and will consequently have a reflection coefficient of $+k$ for 'light' passing in the reverse direction.

Referring now to Fig. 8, which shows some of the images due to the current $+I$ at C_1, the centre of the circle corresponds to the line of intersection of the two mirrors and coincides with the line of springs in Fig. 5. As a result of multiple reflections, a series of images is formed round the circle, those connected by full lines being formed by reflections at the semi-transparent mirror of reflection coefficient $-k$ and at the opaque mirror for which $k = +1$. Those images connected by broken lines are

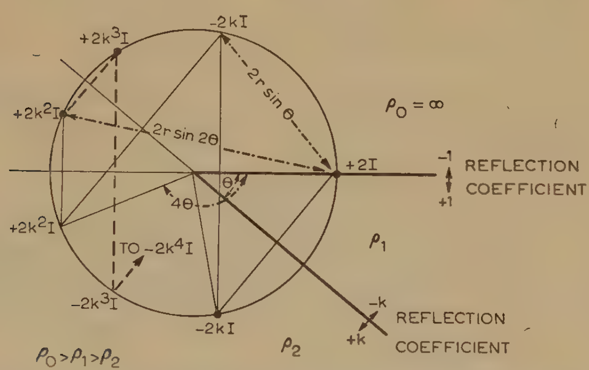


Fig. 8.—Diagram illustrating the formation of electric images by multiple reflections between inclined plane reflecting boundaries.

formed by light passing in the reverse direction, when the coefficients of reflection are $+k$ and -1 respectively. Fig. 8 depicts the special practical case when the source I is coincident with the ground/air boundary, which has a reflection coefficient of unity. As a consequence, the effective intensity of the source becomes $2I$ and the total number of possible images is halved. This follows because there is no virtual image of I above the ground surface to act as a separate source with its own independent series of images.

The following conditions then pertain:

(i) Each pair of images is of strength $2k^nI$.

(ii) Each pair of images is situated $2r \sin n\theta$ from the source, where r is the distance of the station from the line of intersection of the reflecting boundaries and θ is the angle between them.

(iii) Each pair of images and the source subtend an angle of $2n\theta$ at the centre of the circle.

(iv) Many pairs of images are neutralized (as, for example, $\pm 2k^3I$ in Fig. 8). When higher orders are not neutralized, they can usually be neglected because k is less than unity and consequently the image intensities soon become negligibly small.

(v) The total number of images depends on the ratio of π to θ. But whereas the number of images must necessarily be a whole number, the ratio π/θ will, in general, be fractional.

In practice, the effective number of images n_e is given by the largest integer less than π/θ. This number includes the first image to occur in the back angle, and it determines the upper limit of integration in eqn. (4).*

It is now possible to calculate approximately the potential at any point P due to the series of electric images arising from the current I passing between the electrodes C_1 and C_2, and thence to determine the potential difference V between any two particular points, such as P_1 and P_2:

From Fig. 7 it follows that

$$V_{P1} = \left[\frac{\rho_1(2I)}{4\pi(a-b)} + \frac{\rho_1(2I)}{4\pi}\sum_{n=1}^{n=n_e} k^n/d_1\right] + \left[\frac{\rho_1(-2I)}{4\pi(a+b)} + \frac{\rho_1(-2I)}{4\pi}\sum_{n=1}^{n=n_e} k^n/d_2\right]$$

where $d_1 = [(a-b)^2 + (2r\sin n\theta)^2]^{1/2}$

and $d_2 = [(a+b)^2 + (2r\sin n\theta)^2]^{1/2}$

Therefore $V_{P1} - V_{P2} =$

$$\frac{2bI\rho_1}{\pi(a^2-b^2)}\left[1 + \frac{a^2-b^2}{b}\sum_{n=1}^{n=n_e/2} k^n\left\{[(a-b)^2 + (2r\sin n\theta)^2]^{-1/2} - [(a+b)^2 + (2r\sin n\theta)^2]^{-1/2}\right\}\right]$$

By using eqn. (2) and putting $b/a = \alpha$ and $(r\sin\theta)/a = h/a = \beta$ this reduces to

$$\frac{(V_{P1} - V_{P2})}{I}\frac{\pi(1-\alpha^2)}{2\alpha}a = \rho_s =$$

$$\rho_1\left[1 + \frac{1-\alpha^2}{\alpha}\sum_{n=1}^{n=n_e/2} k^n\left\{\left[(1-\alpha)^2 + \left(2\frac{\sin n\theta}{\sin\theta}\beta\right)^2\right]^{-1/2} - \left[(1+\alpha)^2 + \left(2\frac{\sin n\theta}{\sin\theta}\beta\right)^2\right]^{-1/2}\right\}\right] \quad (4)$$

When θ becomes zero, the summation limit goes to infinity and eqn. (4) reduces to eqn. (3) for parallel strata. Eqn. (4) is comparable with Unz's[15] eqn. (16) derived for the Wenner method using equally-spaced electrodes.

The complicated relationships between the points of inflection and peak values of the graphs of eqn. (4) and the actual values of k, θ and h have been determined from the solutions of the equation $d^2\rho_s/da^2 = 0$. These solutions were obtained by methods similar to those used for parallel strata.[4]

(3.4) Results

The graphs obtained at the four stations shown in Figs. 5 and 6 are reproduced in Fig. 9. It is at once apparent that the graphs for the two upper stations are characterized by a high-resistance layer ρ_1—the dry limestone—which overlies a lower-resistance one ρ_2—the wet limestone. The reflection coefficient $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ is therefore negative. This is contrasted with the graphs for the two lower stations, where k is positive and a relatively low-resistance deposit—the conglomerate—overlies the same wet limestone.

The resistivity of the top-soil (the abscissa value when

* If more images are included, values of ρ_s become negative and the graphs pass into the third quadrant.

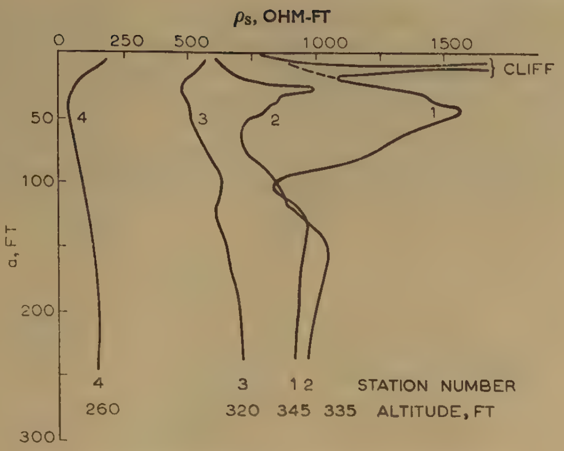


Fig. 9.—Graphs of the four stations on Link Batch.

$a \to$ zero) shows a progressively lower value as the altitude of the station gets less.

The values of ρ_s for the larger values of a are not, as in the case of two parallel strata, simply related to the resistivity ρ_2 of the lower stratum. They are fractional values of the resistivity ρ_1 of the upper deposit for negative values of k and multiple values of ρ_1 when k is positive. Furthermore, they are also functions of the distance r of the station from the line of springs, i.e. from the apex of the angle θ.

Another point of interest arises when it is realized that the difference in the depths of the water-table below stations 1 and 2, namely 14 ft (α and k both being equal to about $0 \cdot 5$), exceeds their difference in altitude, namely 10 ft, the thicker layer of dry limestone being beneath the upper station. Consequently the water-table slopes upwards to the line of springs which rise to the surface between stations 2 and 3 (see footnote to Section 3.1).

In a similar way, the thickness of the conglomerate decreases in the uphill direction and its boundary tends to intersect the hillside approximately along the same line of springs. These conclusions are drawn to scale in Fig. 10.

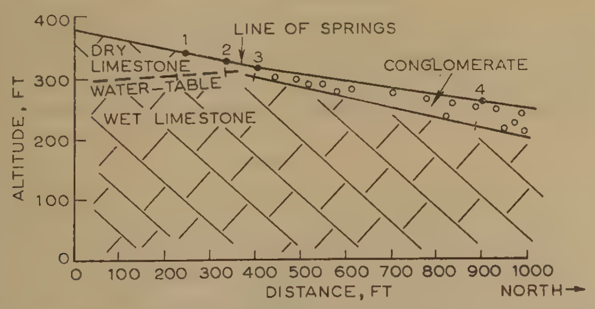


Fig. 10.—S–N section on Link Batch from geoelectric measurements.

(4) PEN PARK HOLE

In August, 1956, a geoelectric survey was undertaken at the request of the City Engineer at Bristol. It was thought probable that a large cavern was situated somewhere beneath certain fields upon which it was proposed to build houses. There was no evidence on the surface to suggest where such a cavern might be, but early records (18th century) referred to a deep rift which opened out into a large cave. The rift had been closed after the death in 1775 of a Canon of Bristol Cathedral who fell down the rift into a lake at the bottom of the cavern.

The purpose of the survey was to locate the cavern, and, if possible, to determine the thickness of the limestone at the point where the roof of the cave came closest to the surface.

(4.1) Historical

The cavern in question is known as Pen Park Hole; a description, with a survey undertaken by a Mr. White in 1779, was written by Mr. A. S. Catcott and published by Rudhall of Bristol in 1792. This survey indicates the main entrance to the cavern—the rift mentioned above—and two other entrances. One entrance was down a shaft into a miners' artificial tunnel. This was known as the Eastern Entrance and was probably made and used by medieval lead miners. The other entrance was west of the main rift. All three entrances had disappeared leaving no trace on the surface, but gruffy ground indicated the probable line of a long rift which extended approximately E–W across the countryside.

With the help of White's original survey (preserved in the Bristol Reference Library) the position of the first station was decided upon. This site subsequently proved to be only about 50 ft from the highest point of the main chamber.

(4.2) Local Geology

The interpretation of graphs of geoelectric data needs to be guided by a knowledge of the local geological structure. For example, the presence of a fault will produce a graphical variation which will be superimposed upon the variation produced by any other anomaly. This superposition of two anomalies may result in a distortion or in a change of magnitude of the effects produced by either anomaly separately. The interpretation of complex variations is often extremely difficult unless one of them can be recognized and its effect appreciated.

In a similar way, surface effects produced by cliffs, quarries or railway cuttings may be so great as to mask the smaller effect of the particular anomaly being studied. See, for example, the top part of the graph for station 1 in Figs. 6 and 9.

For this reason it is advisable to obtain at some nearby site a graph characteristic of the locality, and then survey the anomaly, such as a cave, salt dome, lead vein, etc. The second graph can be compared with the standard or characteristic graph of the immediate neighbourhood, and the form of the graphical kink due to the anomaly can be appreciated and properly interpreted.

In the neighbourhood of Pen Park Hole the limestone protrudes as an anticline in a surrounding 'sea' of Liassic clay which overlies it at its lower reaches. In many of the traverses, one current electrode may be above limestone whilst the other is in the Lias. This will cause a distortion in the lines of current flow, the current naturally concentrating on the path of least resistance. Similarly, the current would tend to flow in any low-resistance path when such a path was presented to it. Cases of this kind need considerable caution and much experience to interpret their graphs. A good example arose when an attempt was made to trace a tunnel under Pen Park Road. One traverse happened to run almost along a buried water main. This presented a very low-resistance path along which the current flowed, with the result that the effect of the underlying tunnel was completely masked.

In the neighbourhood of Pen Park the Liassic clay becomes thicker and thicker the farther it is from the limestone outcrop. If caves occurred in the limestone underneath the clay, they would be a long way below the surface and masked by the very low resistance of the clay overburden. Consequently it is unlikely that they could be detected by a geoelectric method. Reference was made to this geological situation when considering the results in Section 2.5.

(4.3) Theory

J. N. Hummel in 1930 obtained an equation for the apparent resistivity of a spherical cavity in a homogeneous medium.[5]

But he treated the special case of fixed current electrodes spaced apart a distance equal to four times the depth of the cavity, and such a very special case is of little use since it presupposes a knowledge of the depth of the cavity. In 1953 Van Nostrand[18] using bipolar co-ordinates considered the case of a buried conducting sphere and came to the conclusion that it is not feasible to detect a conducting body buried to a depth greater than the mean of its linear dimensions. This is not borne out in practice with high-resistance bodies.

A different treatment yielding an equation comparable with eqns. (3) and (4) was published in 1954.[19] A sphere of radius r full of air of infinite resistivity was considered to be buried with its centre at a depth h below the horizontal boundary of a medium of resistivity ρ, the half-space above the boundary being air.

The result obtained using the comparable analogy of an electric doublet in an unbounded medium of the same resistivity was

$$\rho_s = \rho\left\{1 + \frac{\beta^3(1-\alpha^2)(r/h)^3}{\alpha^3(1+\beta^2)^{3/2}[1+(\beta/\alpha)^2]^{3/2}}\right\} \quad . \quad (5)$$

where $\alpha = b/a$ and $\beta = h/a$.

The form of the graph produced by this particular anomaly is

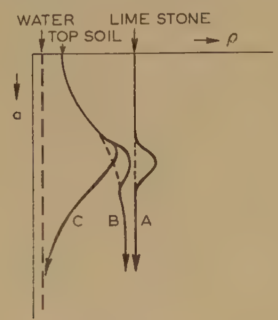


Fig. 11.—Theoretical graphs showing the effect of
A. A high-resistance cavity in a homogeneous medium.
B. A high resistance cavity in a two-layer system.
C. As for B but with water in the bottom of the cavity.

shown in curve A, Fig. 11. By equating to zero the first differential with respect to a, the equation

$$h = \sqrt{(\alpha)}a_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

is obtained, a_0 being the value of a for the maximum (or minimum) value of ρ_s. Thus, since α is less than unity, it is apparent that the anomalous bulge appears lower down on the graph than the depth of the cavity from the surface.

When the cavity is in, say, limestone covered with a thin layer of relatively low-resistance top-soil, the graph takes the form shown in curve B of Fig. 11. Curve C shows the effect of water in the bottom of the cavity. Although the water may be only a few inches deep, its resistivity (especially in limestone caves) is very low. Consequently, the sheet of water acts like an electric screen (a copper sheet, for example). Hence, although the presence of water can be detected quite easily, its depth cannot be measured by geoelectric methods. In other words, the graph does not bend back to the normal value for limestone, but continues indefinitely downwards at the low value of the resistivity of water. This effect was discussed when referring to wet broken chalk in Section 2.

(4.4) Survey

Work was commenced on the 7th August, 1956, and by the 15th August the main cavern had been located and a lake was detected at the north-east end of the cave. The original Rift Entrance and the position of the shaft leading to the Eastern Passage were also located. The Eastern Passage, by a series of short traverses, was traced from the bottom of the shaft to where it entered the main chamber.

These conclusions were based upon 800 readings at 40 stations (Fig. 12) taken over a period of 7 days. Measurements were

Fig. 12.—Distribution of stations round Pen Park Hole.
—|—|—| Clay/limestone boundary.

made to depths of 400 ft on the traverses over the main chamber, but only to 150 ft when tracing the course of the higher passage and when locating the original entrances. The Western Entrance was not located and may possibly have been covered by a new roadway or may be obscured by a nearby and recent hedgerow.

(4.5) Results

Even if it were desirable, it will not be possible to show all the graphs arising from this survey. Fig. 13 shows two typical graphs obtained from traverses above the main cavern. These are marked 5 and 6. The graph of station 5, which is comparable to curve C in Fig. 11, indicates the presence of water at the bottom of a large cave. At station 6 the lower portion of the graph tends to become asymptotic to $\rho_s \simeq 1\,500$, and consequently the water below station 5 does not extend below station 6. Station 5 was situated north of station 6. Subsequently it was found that the lake was confined to the north-eastern portion of the cave. For these graphs α was equal to 0·2; hence, using eqn. (6) and a value of a_0 of about 70 ft, the thickness of the cave roof in the neighbourhood of station 6 appears to be $\sqrt{(0 \cdot 2)} \times 70$, or just over 30 ft. This has not yet been verified by internal measurements.

The three graphs 32, 27 and 19 in the top left-hand corner of Fig. 13 were taken over the Eastern Passage leading to the bottom of a filled-in mine shaft. The graph obtained almost immediately above the mine shaft is numbered 34. It will be noticed that the high-resistance tunnel or passage gets larger as it gets

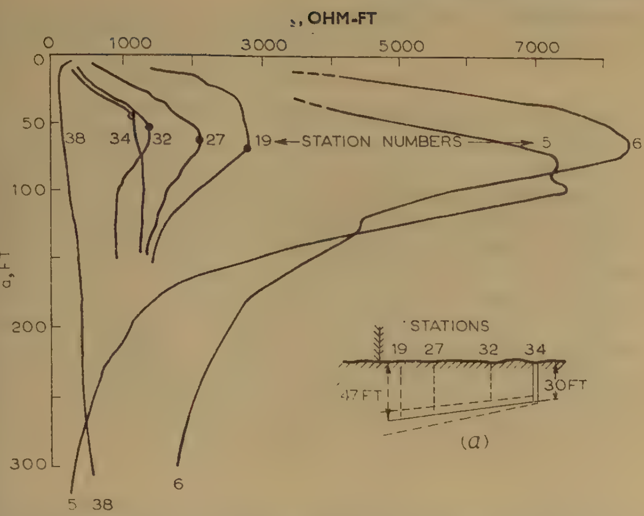


Fig. 13.—Graphs for two stations above Pen Park Hole, for four stations above the shaft and Eastern Entrance and for one station on the Liassic clay.

deeper, while the shaft yields a typical vertical limestone graph up to $a \simeq 50$, above which the value of ρ steadily decreases to the low value of the in-filling. The depth of the shaft, with $\alpha = 0{\cdot}4$ for these particular traverses, is therefore $\sqrt{(0{\cdot}4)} \times 50$, or about 30 ft. The junction of the miners' tunnel with the shaft was subsequently found at this depth. Fig. 13(*a*) is a rough sketch showing the section as deduced from these four graphs.

Finally, station 38 was one of several sited over the Liassic clay at some distance from the limestone outcrop. The graph is interesting as being typical of an almost homogeneous low-resistance medium. A more detailed inspection indicates that the upper parts of the clay were probably wetter than the lower parts, whilst the top-soil has a resistivity comparable with that above the other stations. For these low-resistance localities it was convenient to make α equal to $0{\cdot}8$.

(4.6) Excavations

The above conclusions having been drawn by interpreting the graphs from the 40 stations, it was felt desirable to test them by actual excavations. Consequently it was decided to try to open up the Eastern Entrance because the work involved in attempting to open the main Rift Entrance would not only be too long a task but would probably be very dangerous. Excavation was commenced at Station 34, and the original miners' shaft was reached at a depth of about 5 ft from the surface. The station had been sited almost exactly above the centre of the shaft. When the infilling of recent rubble was first removed, the passage predicted in Fig. 13(*a*) was missed by about 3 ft, and a lot of unnecessary digging was undertaken before a clay choke was located at a depth of 32 ft. When cleared, this led directly into the Eastern Passage, which followed the course already mapped by the geoelectric surface measurements. As suspected, the passage terminated on the side of the main chamber. The bottom of the cavern was reached at a depth of over 150 ft from the surface. A lake of muddy water was found at the north-east side below those stations which indicated the presence of water on their graphs. The exploration of the cavern and its several side-passages is continuing.

(5) ACKNOWLEDGMENTS

The extensive field work involved in the three examples of geoelectric surveys described in Sections 2, 3 and 4 could not have been undertaken had it not been for the ready assistance I received from many colleagues, students and other friends interested in the work.

As will be appreciated, in order to carry out a geoelectric investigation by the technique adopted in these surveys, a team of at least six persons is desirable. It is therefore with much gratitude and pleasure that I am able to record my thanks to all those concerned, and in particular to the following:

Throughout the survey on the Holderness Plain, Mr. J. M. Hough, of the Physics Department at Hull University (then the University College), assisted with both the theoretical work and with the practical measurements in the field. During the later part of the time Mr. L. F. Penny, Head of the Geological Department, helped with the geological interpretation and joined the team in the field work. The team was always made up with other colleagues and occasional research students, and in particular Mr. A. L. Binns, whose regular attendance and help in providing some of the essential transport was always greatly appreciated.

The Mendip survey was carried out with members of the University of Bristol Spelaeological Society, who have always been willing to help when help was needed.

At Pen Park Hole, Brigadier E. A. Glennie, Dr. E. K. Tratman, and two Bristol Corporation Surveyors—Messrs. E. J. Biddlecombe and F. A. Edwards—together with others from the City Engineer's Survey Department, carried out the work on the 40 stations mentioned in Section 4. I am also indebted to the City Engineer, Mr. J. B. Bennett, and the Assistant City Engineer, Mr. W. Johnson, for help with material, fencing and timbering round the shaft. The actual excavations were carried out by members of three Bristol caving clubs—the Bristol Exploration Club, the University of Bristol Spelaeological Society and the Wessex Caving Club, led by Messrs. Paul Dolphin with E. Bagshaw (B.E.C.), B. R. Collingridge (U.B.S.S.) and F. Frost (W.C.C.). Later, Dr. Oliver Lloyd took over from Mr. Paul Dolphin when the latter went abroad.

Finally, I would again like to express my thanks to the Royal Society for a grant covering the cost of the instruments and some of the accessory equipment.

(6) REFERENCES

(1) Wenner, F.: 'A Method of Measuring Earth Resistivity', *Bulletin of the U.S. Bureau of Standards*, 1916, **12**, p. 469.

(2) Tagg, G. F.: 'A Resistivity Survey in the Wash Area', *Journal I.E.E.*, 1957, **3**, p. 5.

(3) Huber, A.: 'Some New Developments of the Geoelectrical Resistance Method', *Elektrotechnik und Maschinenbau*, 1952, **69**, p. 1.

(4) Palmer, L. S., and Hough, J. M.: 'Geoelectrical Resistivity Measurements', *Mining Magazine*, 1953, **88**, p. 16.

(5) Hummel, J. N.: 'A Theoretical Study of Apparent Resistivity in Surface Potential Methods', American Institute of Mining and Metalurgical Engineers, Technical Publication No. 418, 1930.

(6) Lancaster-Jones, E.: 'The Earth Resistivity Method of Electrical Prospecting', *Mining Magazine*, 1930, **42**, p. 355 and **43**, p. 19.

(7) Whitehead, S., and Radley, W. G.: 'Experiments Relating to the Distribution of Alternating Electric Current in the Earth and the Measurement of the Resistivity of the Earth', *Proceedings of the Physical Society*, 1935. **47**, p. 589.

(8) Tagg, G. F.: 'Interpretation of Resistivity Measurements', American Institute of Mining and Metalurgical Engineers, Technical Publication No. 755, 1937.

(9) BISAT, W. S.: 'The Older and Newer Drift in East Yorkshire', *Proceedings of the Yorkshire Geological Society*, 1940, **24**, p. 137.

(10) BISAT, W. S., and BELL, J. A.: 'The Occurrence of a Bed Containing Moss in the Boulder-clays of Dimlington', *ibid.*, 1940, **24**, p. 219.

(11) PALMER, L. S.: 'Holderness in the Making' from 'A Guide to the East Riding of Yorkshire' (University College of Hull, 1939).

(12) HABBERJAM, G. M., and WHETTON, J. I.: 'A Resistivity Investigation of Glacial Deposits near Bear Park, Co. Durham', *Proceedings of the Yorkshire Geological Society*, 1954, **29**, p. 255.

(13) ALDREDGE, R. F.: 'The Effect of Dipping Strata on Earth Resistivity Determinations', *Colorado School of Mines Quarterly*, 1937, **32**, p. 171.

(14) SKALSKAYA, I. P.: 'Field of a Point Source of Current Situated on the Earth's Surface above an Inclined Stratum', *Journal of Technical Physics* (U.S.S.R.), 1948, **18**, p. 1242.

(15) UNZ, M.: 'Apparent Resistivity Curves for Dipping Beds', *Geophysics*, 1953, **18**, p. 116.

(16) MAEDA, K.: 'Apparent Resistivity for Dipping Beds', *ibid.*, 1955, **20**, p. 123.

(17) DE GERY, J. C., and KUNETZ, G.: 'Potential and Apparent Resistivity over Dipping Beds', *ibid.*, 1956, **21**, p. 780.

(18) VAN NOSTRAND, R. G.: 'Limitations on Resistivity Methods as Inferred from the Buried Sphere Problem', *ibid.*, 1953, **18**, p. 423.

(19) PALMER, L. S.: 'Location of Subterranean Cavities by Geoelectrical Methods', *Mining Magazine*, 1954, **91**, p. 137.

(20) STEFANESCO, S., and SCHLUMBERGER, C. and M.: 'Electric Potential Distribution around a Point in the Earth', *Journal de Physique et le Radium*, 1930, *I*, p. 132.

(21) MUSKAT, M.: 'Potential Distribution about an Electrode on the Surface of the Earth', *Physics*, 1933, **4**, p. 129.

(22) BUCHHEIM, W.: 'Evaluation of Geoelectric Depth Soundings by an Integral Equation Method', *Wissenschaftliche zeitschrift der Techischen Hochschule Dresden*, 1952/3, **2**, No. 3, p. 337.

(23) LOGN, Ö.: 'Mapping nearly vertical Discontinuities by Earth Resistivities', *Geophysics*, 1954, **19**, p. 739.

(7) APPENDIX

The chief theoretical problems involved in geoelectric surveying are (i) the derivation and evaluation of the potential functions $\rho_s = f(V)$ or $f(R)_{I\,const}$ for different electrode configurations and for specific geological anomalies, and (ii) the solutions of the differential equations $d^2(\rho_s)/da^2 = 0$ and $d(\rho_s)/da = 0$, leading to relationships between the depths of anomalies and the values of a for points of inflection and for changes in gradients of the graphs of the potential function.

Ability to derive the potential equation for a given geological anomaly depends to some extent on the simplicity of the electrode configuration. Some authorities[20–23] attack the problem by the direct solution of Laplace's equation involving Bessel functions, or deduce the potential distribution over the earth's surface as a real integral leading to more or less rapidly converging series. These fundamental methods are of considerable academic interest but of less practical value in the field than the solutions (sometimes only approximate) which arise by the use of Maxwell's method of electric images. Although the solutions of equations derived by this method also involve the summation of series, they have been found more convenient in practice and therefore have been adopted for the derivation in this Appendix of eqns. (2), (3) and (5).

(7.1) The Derivation of Eqn. (2)

Assuming that the potential field at a distance d from a point source of strength I in a homogeneous medium of resistivity ρ is $\rho I/4\pi d$, then for a half-space with a source on the boundary, this becomes $\rho I/2\pi d$ because the effective current strength is $2I$, the strength of the original source plus that of its electric image in the boundary. This assumes the boundary is a perfect reflector, which will be the case if the resistivity of the medium above the boundary is infinite, as for air.

With a source C_1 and a sink C_2, both on the boundary and separated by a distance $2a$, the potential at a point P on the line joining the source to the sink and situated a distance $(a - b)$ from the source and $(a + b)$ from the sink, will be

$$V_P = \frac{\rho I}{2\pi}\left(\frac{1}{a-b} - \frac{1}{a+b}\right)$$

Consequently the difference in potential between two points P_1 and P_2 situated symmetrically between the points C_1 and C_2 will be

$$(V_{P1} - V_{P2}) = \frac{\rho I}{2\pi}\left[\left(\frac{1}{a-b} - \frac{1}{a+b}\right) - \left(\frac{1}{a+b} - \frac{1}{a-b}\right)\right] = \frac{\rho I}{\pi}\frac{2b}{a^2 - b^2}$$

On substituting α for the ratio b/a and solving for ρ we get

$$\rho = \frac{\pi(1-\alpha^2)}{2\alpha}a\frac{V}{I} \text{ or } \frac{\pi(1-\alpha^2)}{2\alpha}aR$$

which is eqn. (2). Eqn. (1), for the Wenner technique, is the special case when $\alpha = 1/3$.

(7.2) The Derivation of Eqn. (3)

This equation gives the potential function for two parallel strata, the upper or superficial layer being of thickness or depth h and of resistivity ρ_1, and the lower being of infinite thickness and of resistivity ρ_2. Following the optical analogy, the reflection coefficient of the earth/air boundary will be $(\infty - \rho_1)/(\infty + \rho_1)$, or unity. This assumes the resistivity of the air above the boundary is infinite. The reflection coefficient k for the boundary between the parallel layers will be $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ for 'light' passing from the upper to the lower medium. Electric images of the source $2I$ will be of intensity $2kI$ at distances $2h$ above and below the earth/air boundary. These primary images will produce secondary images of strength $2k^2I$ at distances $4h$ above and below the surface boundary, and so on. (See Fig. 14.)

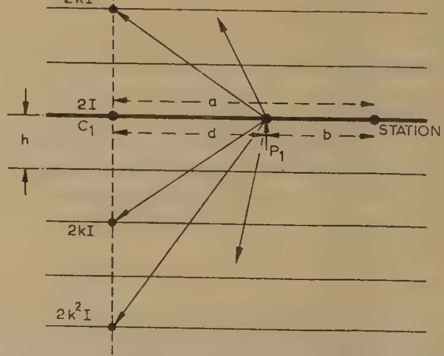


Fig. 14.—Electric image system for two parallel strata.

These additional sources will all contribute to the potential at a point P_1 situated on the surface at a distance d from the source. Thus the potential at P_1 will be

$$V_{P1} = \frac{\rho I}{2\pi}\left\{\frac{1}{d} + 2\sum_{n=1}^{n=\infty} k^n[d^2 + (2nh)^2]^{-1/2}\right\}$$

There will be a similar contribution but of opposite sign to the potential at P_1 if a sink is also situated on the boundary. Now let it be supposed that a source $2I$ at C_1, and a sink $-2I$ at C_2 are placed on opposite sides of a station S, so that $C_1S = SC_2 = a$. Also let two potential points P_1 and P_2 be similarly placed but at distances b from the station, all five points being in a straight line. Also let $b/a = \alpha$ and be less than unity. Then, to determine the difference of potential between P_1 and P_2, it will be necessary to subtract the total field at P_2 (due to both source and sink and their respective images) from the total field at P_1. There will be four terms similar to that given above for V_{P1}, but with d replaced by either $(a - b)$ or $(a + b)$. The resulting algebraic summation is

$$(V_{P1} - V_{P2}) = \frac{\rho I}{\pi a}\frac{2\alpha}{(1-\alpha^2)}$$

$$\left[1 + \frac{\alpha}{(1-\alpha^2)}\sum_{n=1}^{n=\infty} k^n\{[(1-\alpha)^2 + (2n\beta)^2]^{-1/2} - [(1+\alpha)^2 + (2n\beta)^2]^{-1/2}\}\right]$$

in which $\beta = h/a$. Eqn. (3) now follows directly by substituting from eqn. (2) in the first part of this expression.

Each one of the family of curves represented by eqn. (3) has one point of inflection which will have some ordinate value a_0, say. If the relationship between a_0 and h could be determined, the thickness h of the upper stratum could be calculated from a knowledge of a_0 taken from the graph. The required relationship can be obtained by solving the equation

$$d^2(\rho_s)/da^2 = 0$$

This is not easy to do, but graphical solutions have been obtained (see Reference 4, Fig. 2) for different values of α and k. A very approximate solution useful for rough field work is $h = 0{\cdot}5a_0$, but as the ratio of h/a_0 depends on the values of both α and k, any more exact relationship must be read off the (α, β) graph for the correct value of k. For example, with $k = -0{\cdot}5$ and $\alpha = 0{\cdot}8$, the value of β is $0{\cdot}47$, i.e. $h = 0{\cdot}47a_0$. With $k = +0{\cdot}5$ and the same value of α, β is equal to about $0{\cdot}35$, or $h = 0{\cdot}35a_0$. If $\alpha = 0{\cdot}9$ with $k = -0{\cdot}5$, the ratio h/a_0 drops from $0{\cdot}47$ to $0{\cdot}33$. In general, the higher the values of α or k, the smaller will be the ratio h/a_0.

(7.3) The Derivation of Eqn. (5)

The derivation of the potential function for a sphere of radius r buried to a depth h in a medium of resistivity ρ is most easily carried out by replacing the sphere with an electric doublet Q and its image Q′ situated a distance h below and above the boundary respectively. The two half-spaces are replaced by a homogeneous medium of resistivity ρ and of infinite extent. The current source and sink must be doubled in intensity as before. This is a common hydrodynamic problem, and the potential at any point P is given by

$$V_P = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2} + \frac{ad_0r^3}{(a^2+h^2)^{3/2}}\left(\frac{1}{d_3^3} + \frac{1}{d_4^3}\right)\right]$$

where the distances d and a are as shown in Fig. 15.

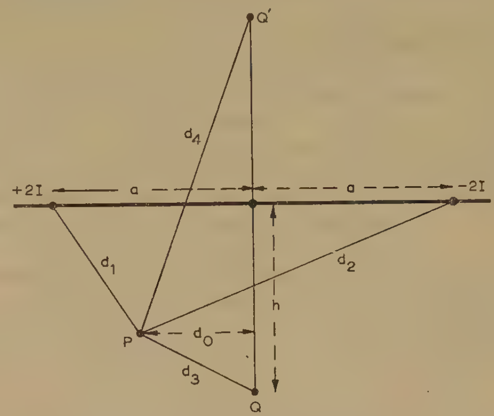


Fig. 15.—Electric doublet and image system for a sphere buried in a homogeneous medium.

To obtain the potential difference between two points P_1 and P_2 situated distances $+b$ and $-b$ from the origin on the line joining the source and sink, d_0 becomes $+b$ or $-b$ and the other values of d are the respective radius vectors of P_1 and P_2.

On making the appropriate substitutions in the above value for V_P we get

$$(V_{P1} - V_{P2}) = \frac{2\alpha\rho I}{\pi(1-\alpha^2)a}\left\{1 + \frac{\beta^3(1-\alpha^2)(r/h)^3}{\alpha^3(1+\beta^2)^{3/2}[1+(\beta/\alpha)^2]^{3/2}}\right\}$$

where $\alpha = b/a$ and $\beta = h/a$ as before. Eqn. (5) now follows directly by substituting from eqn. (2) in the first part of this expression. It may be noted that, in the absence of the sphere, i.e. when either $r \to 0$ or $h \to \infty$, the above equation reduces directly to eqn. (2) for a homogeneous medium.

DISCUSSION BEFORE THE MEASUREMENT AND CONTROL SECTION, 3RD FEBRUARY, 1959

Professor S. K. Runcorn: The surveys most frequently made by geophysicists are magnetic and gravitational. These are mainly of use to the oil industry, where it is very important to obtain information of the structure of strata at fair depths. On the other hand, the geoelectric survey is not usually very effective in determining the structure at great depths, although, as the author points out, it is extremely efficient in detecting, for instance, the depth of bedrock. Such surveys thus have considerable application to engineering geology.

It is worth noting that there is a fundamental difficulty in inferring the structure of the rocks below the earth's surface by geophysical survey. This is well illustrated by considering the gravitational or magnetic cases, in which the intensity of the earth's gravitational field or the strength of one of the components of the earth's magnetic field is measured over the surface. One then has to solve an inverse potential problem, i.e. to determine what spatial variations of attracting matter can account for the observed field variation at the surface.

It is important to realize that there is an essential ambiguity. For example, suppose that a gravitational survey is made over a surface below which is a substratum of rather dense rock which has been faulted. The disturbance will cause an anomaly in the earth's gravitational field, and the variation observed as one moves across the surface will be fairly sharp. If this discontinuity is much deeper, the field variation at the surface is much smoother but this same variation could equally well result from a more gradual change of density laterally at a shallower depth. Thus it is impossible to infer from the surface survey the depth of the

attracting body unless the geology of the region gives some information about the body causing the field disturbance at the surface.

To me, the most interesting theoretical aspect of the geoelectric survey is that there is not this ambiguity in the interpretation problem. If a survey is made in which the distance between the electrodes is varied, one can in theory plot unambiguously the variation of conductivity with depth. One must still interpret the results in terms of geology, but the fundamental ambiguity present in the magnetic and gravitational cases is absent in the geoelectric case.

One of the difficulties with this kind of survey is that one cannot go very deep: if the ground is homogeneous in conductivity, it is fairly easy to show that half the inter-electrode current flows above a depth equal to half the distance between the electrodes. Thus, to obtain information to the depths which interest the oil geologist—say 10000 ft—one must have very considerable lengths of cable connecting the electrodes. But it is worth noting that use has been made of telluric currents to overcome this limitation. In this method one takes advantage of the fact that there are natural earth currents which flow on a global scale, arising from electromagnetic induction by the geomagnetic variations which, in turn, are due to varying electric currents flowing in the ionosphere. Some use has been made, and probably in the future a lot more use will be made, of these natural earth currents to make inferences about the sub-surface geological structure. If the ground is uniform in conductivity, the current density will be uniform over the surface; but if, for example, there is a salt dome of high resistivity, the lines of current flow will be bunched together over the dome. Thus, if the potential differences are measured over different distances at the surface, one would expect to be able to plot the shape of the structure.

One of the great difficulties in making geoelectric measurements is that a cell is set up when contact is made with the ground, and electrochemical theory indicates that it is very easy at the contact between the electrode and the ground to obtain spurious potentials of a fraction of a volt. Various people have tried to get over this by having special non-polarizable electrodes, but the problem has not been solved satisfactorily, and a good deal more work is needed. Of course, this problem of contact potentials is serious only with slowly varying earth currents, and the author overcomes the difficulty by using a very low-frequency supply.

Mr. J. H. Morgan: In making practical use of the geoelectric method I have found that, where there is a simple problem to solve, the solution is easy to find and unique; but where there are complicated geological structures, the problem takes on some complexity and one finds difficulty in obtaining a unique solution, if one can obtain a solution at all.

Rather than resort to the author's mathematical methods we adopted a technique of plotting the electrode spacing against resistivity on log-log scales. With this technique we can make a model of the strata we expect to find, and then produce curves which are identical with the expected field curves, though translated from them.

This allows us to make, say, a 2-layer model (which is a fairly simple one) and to determine the point on the curve where the electrode separation corresponds to the depth of the discontinuity. We have never attempted any complicated problems, but might not this method to some extent resolve even more difficult strata configurations?

I feel that the main use of this method might be by those who need to know the micro-geology at the site of some engineering works; an architect might want to know how deep to sink his piles, a road constructor how deep is the alluvial clay over hard rock, or an electrical engineer the best zone for his earth plates.

I carried out a survey on Dartmoor, to see whether Taw Marsh was a silted-up lake. Resistivity measurements were taken along the valley flow from south to north and showed the depth of the original granite. A bore-hole was drilled and the change was found to be within 10% of that predicted, which is as close as one could expect from the method. We also found that small variations occurred in our graphs close to streams which had cut small valleys or gorges, and I doubt whether one would be able to use small kinks in the curve in an interpretation.

In many measurements we have found electrophoretic currents in the ground, and detected them by using half-cells designed for corrosion studies. These are accurate within fractions of a millivolt, and I am sure that, if one wanted to measure telluric-current potentials, these techniques would help greatly.

Dr. S. H. Shaw: The Wenner method and modifications of it have a very wide use throughout the world, particularly in water-finding methods. The surveys are used in a number of African territories and elsewhere.

With regard to the survey of Holderness Plain, too much reliance should not be laid on correlations between measurement points as much as two miles apart. The depths of the interglacial gravel have been determined on a purely empirical basis from the high-resistance 'kinks'. However, many glacial gravels are a melange of pebbles, sand and clay, and it is by no means certain that they would be of high resistivity.

A water-table is frequently not horizontal but its elevation at any point is proportional to the head at that point. The water must therefore be flowing from right to left, Fig. 5, and it is therefore quite impossible for any springs to occur at the point shown, which indicates that the diagram is wrong. The author has trusted mathematical interpretation to a very close degree, but we are only given that the difference in the depth of the water table between stations 1 and 2 is 14 ft. What were the calculated depths of the water-table for stations 1 and 2, and how was the difference in the ground elevation between the stations determined? What were the absolute resistivities of the wet and dry limestones as determined by mathematical analysis of the curves?

The scale of Figs. 12 and 13 shows that the dimensions of the cavern are so great in relation to the depth investigated that there is little justification for interpreting the curves on the assumption that the anomalies are analogous to those which would occur with a buried sphere. At stations 5 and 6 measurements were taken to 400 ft, and at least one current electrode must have passed on to Liassic clay. The whole surface in this area was probably much disturbed, and so the measured resistivities are likely to be affected by lateral changes. I therefore disagree with the interpretation of the later parts of curves 5 and 6. In particular, the contention that curve 5 indicates the presence of water in the cavern while curve 6 does not is untenable. Was the resistivity of the water in the cavern measured?

Mr. E. J. Leaton: Another approach to the measurement problem is shown in the simplified circuit diagram (Fig. A). The assumed equivalent circuit of the soil system, below the dotted line, shows the apparent resistance, R_x, which we wish to measure, joined to each electrode by an unknown impedance Z. A dry battery feeds transformer T_1 through vibrator contacts 5, 6 and 7, generating an almost square waveform of voltage which is applied to the soil system through the full winding of potential divider, RV and electrodes C_1, C_2. The voltage across the variable portion of RV, via voltage transformer T_2, opposes the voltage across R_x. Any current flowing in resistors R_1 and R_2 undergoes synchronous rectification at the secondary vibrator contacts 2, 3 and 4. Thus the galvanometer indicates both the magnitude and direction of unbalance.

When RV is adjusted to give zero current indication on the galvanometer, the voltage across the variable portion of RV is

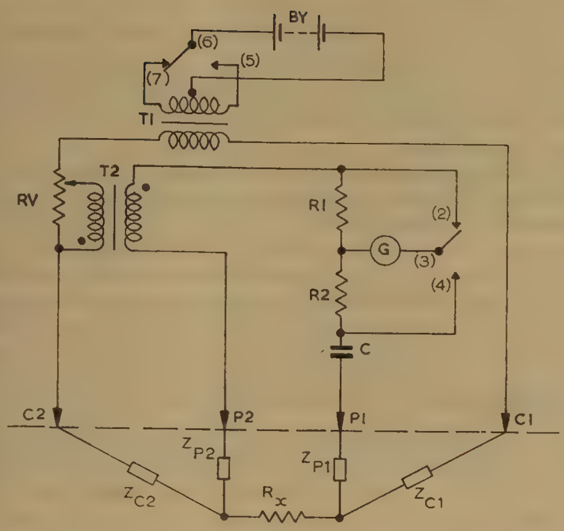


Fig. A.—Circuit of earth-resistance measuring equipment.

equal to that across R_x. Since these carry the same current, their resistances must also be equal, and the value can be read from the calibrated dial of RV. Different ranges can be obtained by changing the ratio of T_2 and by shunting RV.

Electrode impedances Z_{c1} and Z_{c2} alter the current flowing but have virtually no effect on the balance point, and since at null no current flows in P_1 and P_2, neither Z_{p1} nor Z_{p2} has any effect.

The standard vibrator frequency is 110 c/s, so that power-system currents do not affect the readings appreciably, but it is rather high for this kind of measurement. This may cause trouble with high electrode impedances—above about 1 000 R_x—but it does enable the equipment to be comparatively compact and portable, measuring 14 in × 11 in × 5 in, weighing 20 lb with the battery incorporated, and needing only one man to operate it. A switching accessory can be fitted so that the resistance of each electrode may be measured by the well-known 3-terminal method, and further readings can be obtained which assist in the interpretation of difficult soil structures by interchanging the electrode connections.

Mr. F. C. Widdis: There are many alternative devices which can be used for earth-resistivity measurement. The main difficulty which occurs in such measurements is the polarization effect at the electrodes, and this can be eliminated either by the use of alternating current, or by continuously reversing direct current with a hand-driven commutator. A.C. methods have not been extensively used; they require an engine-driven alternator, usually operating at 500 c/s, for the current supply, with an a.c. potentiometer having magnitude and phase balances for the potential measurements. Capacitance currents can cause difficulties in this case.

An equipment which has proved very satisfactory in practice is the so-called milliammeter-potentiometer. This consists of a d.c. potentiometer, a precise milliammeter, a 360-volt dry battery and a hand-driven double commutator for reversing. The milliammeter can be used both to standardize the potentiometer and to measure the earth current. I believe this apparatus will give a somewhat higher accuracy in electrical measurement than that used by the author, but whether this is an advantage in practice is a question for the geophysicist.

Extreme care must be exercised in the design of equipment for use in the field. It is an expensive matter to carry out surveys in remote or inaccessible places, and equipment failure is intolerable. Apparatus should be not only easy to service, but completely resistant to climatic extremes. Special attention must be given to the insulation of any circuit-elements where the relatively high-voltage current leads and the potential-measuring circuits are in juxaposition, since comparatively minute leakage currents can cause serious errors.

Mr. A. C. Lynch: An important application of geoelectric surveys is in the prediction of the voltages liable to be induced in communication circuits in the event of an earth fault on a neighbouring power circuit. The fault current flows in a loop whose size depends on the resistivity of the ground—the higher the resistivity, the larger the loop—and the mutual inductance between the circuits depends on the area of this loop. A geoelectric survey of Britain concerned, of course, with major features only, was made for this purpose in 1934.

Dr. P. Vigoureux: Since telluric currents have a spectrum, might not better results be obtained by measuring this, or part of it, or even by measuring the spectrum of the e.m.f. induced in a coil on the surface, since there is a correspondence between these telluric currents and the p.d.'s in the air above them?

Dr. G. H. Dury (*communicated*): The author states that the Mendip water-table rises towards the surface lines of springs. Can this arrangement be due to local depression of the water-table under the control of springs elsewhere? It is not stated whether or not the springs on site were flowing at the time of observations, which were made during the summer, nor how far underground the downward slope away from the springs is thought to continue. Although phreatic water can follow curved paths, first downward and then upward, it is difficult to imagine that the net path of phreatic water could be upward, even though most peculiar effects of underground flow are acknowledged to occur in well-bedded and well-jointed limestones.

The conglomerate, the outcrop of which controls the position of the spring-line, is described in the Summary as having been laid down in the Triassic Sea. Presumably the Dolomitic Conglomerate is meant; is this not supposed to have originated as desert scree on the flanks of the Mendip inselberg?

The most successful observations in Pen Park Hole are of great geomorphological interest. Does the author know of any comparable observations in chalk country?

Mrs. E. M. Lynch (*communicated*): In Figs. 5 and 10, is the shading representing limestone intended to show the inclination of the strata? It is usually stated that, in order to produce active springs, a water-table must be dome-shaped. It would be interesting to know whether the water-table in the Mendip area is permanently depressed, and, if so, what causes the general upward movement of water towards the spring-line.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Professor L. S. Palmer (*in reply*): Professor Runcorn has rightly stressed the necessity for knowing something of the geology of any area under investigation if an unambiguous interpretation of geoelectrical graphs is to be obtained. Mr. Morgan also refers to the difficulty of obtaining a unique solution in complex cases.

Although I have had no experience with telluric currents, I am of the opinion that isopsephic graphs of surface potentials would not be sufficient to differentiate between the current variations at different depths.

Mr. Morgan's suggestion of using a three-dimensional model can be useful, but I have found considerable difficulty in getting

materials of the required resistivity values scaled down to suit the dimensions of the model.

The use of a log/log plot would exaggerate discontinuities at shallow depths. The value of such a method would appear to depend on the particular objective of the survey.

Concerning Dr. Shaw's remarks: the depths of the interglacial gravels were not 'determined on a purely empirical basis', but by the method described in Reference 4. It is true that some gravels have relatively low resistivities, but this does not apply to the interglacial gravels of the Holderness Plain.

The idea that the water-table below the surface is subject to the normal hydrostatic pressure head similar to water in an open reservoir is incorrect. This is supported by Dr. Dury's remarks. The depth of the water-table at station 1 was about 35 ft and approximately 20 ft at station 2. Station altitudes were surveyed in the ordinary way from local bench marks.

The apparent resistivity of the wet limestone was about 500 ohm-ft and can vary from four to ten times this value for dry limestone.

With regard to Dr. Shaw's comments on Figs. 12 and 13, the ratio r/h in eqn. (5) is not theoretically restricted in its application. Dr. Shaw disagrees with the interpretation of curves 5 and 6, but there *was* in fact water below stations 3, 2 and 5 and *not* below stations 6, 7, 9 and 11. This was verified by subsequent exploration after an entrance had been excavated at station 34.

I am very interested in Mr. Leaton's alternating current method of geoelectrical surveying and particularly in his ingenious method of using transformer T2 (Fig. A) to balance out the a.c. potential across P_1P_2 and then to calibrate the variable resistor RV in ohms. I look forward to trying out this method on archaeological sites in the near future.

I have only used Mr. Widdis's method in the laboratory. It has the merit of simplicity.

Mr. Lynch points out an interesting application of geoelectrical techniques, but I have had no practical experience on the measurement of current leaks.

I am unable to comment on Dr. Vigoureux's suggestion that the frequency of telluric currents may be related to subterranean discontinuities or anomalies.

The behaviour of phreatic water is, as Dr. Dury says, 'most peculiar'. In some way it must be related to capillary action, but this is a matter about which geologists and physicists have not yet produced an agreed solution.

The major constituents of the local conglomerate are water-worn pebbles, but there is a coombe-rock-like matrix at some of the higher levels.

As there are no natural caves in the chalk, the only comparable work to that over Pen Park Hole with which I am acquainted is the survey over a railway tunnel in the chalk wolds described in Reference 19.

With regard to Mrs. Lynch's question, the shading in Figs. 5 and 10 is only intended to indicate very roughly the general dip of the limestone beds in the Link Batch neighbourhood. I am unaware whether the Mendip water-table ever becomes elevated above the line of springs which occurs along the junction of the limestone and conglomerate. The level of the water-table certainly varies. but no specific measurements of this variation have yet been undertaken by geoelectric methods.

621.311.17 : 621.316.9

The Institution of Electrical Engineers
Paper No. 2699 U
Aug. 1958

ELECTRICAL INSTALLATION AT CALDER HALL NUCLEAR POWER STATION

By N. J. MACKAY and E. HARDWICK, Associate Members.

(*The paper was first received* 21*st February, and in revised form* 19*th May*, 1958. *It was published in August*, 1958, *and was read before the* NORTH SCOTLAND SUB-CENTRE *at* DUNDEE 11*th December, the* NORTH SCOTLAND SUB-CENTRE *at* ABERDEEN 12*th December*, 1958, *the* SOUTH-EAST SCOTLAND SUB-CENTRE 6*th January, at a meeting of the* UTILIZATION SECTION 15*th January, held in conjunction with the* BRITISH NUCLEAR ENERGY CONFERENCE, *the* RUGBY SUB-CENTRE 28*th January, and the* NORTH MIDLAND UTILIZATION GROUP 17*th February*, 1959.)

SUMMARY

The paper describes the essential features of the installation with particular regard to the security of the supplies to the reactors. Main connections to the Grid system and the method of electrical control are included.

Details are given of the electrical equipment required for the normal operation of the reactors and also for emergency operation, should the main supply fail. The method of change-over from normal to emergency running is explained in some detail, since it affects the safety of the reactor and must be reliable.

The paper also briefly outlines the way in which some of the special problems were approached and indicates the reasons for the particular solution employed.

(1) INTRODUCTION

Since Calder Hall was the first attempt to produce electrical energy from a nuclear source on anything approaching a commercial scale, it provided such a problem from the electrical design aspect that, while some aspects were bound to be novel, anything which could be adapted to standard and well-tried methods obviously should be, so minimizing one hazard in a chain of novel application.

Because it is undesirable to subject a reactor to the thermal cycle incurred in incipient tripping and consequent restarting, and because it is essential that some cooling be maintained for a considerable time after shut-down, maximum security of supply is a paramount requirement, and both the arrangement of the supply and the location of the equipment have been directed to meet these conditions. Also as an overall requirement, a limitation is placed on the rate of control-rod withdrawal in the interests of reactor safety, and this limits the rate at which a reactor can be brought back on load after a complete shut-down. Therefore both power supplies and instrument systems must be designed to prevent spurious tripping. This has obviously led to a complete departure from the unit principle of supply, in that loss of generation cannot be countenanced as a reason for failure of supply to the reactors, and in effect, the normal supply is guaranteed by duplicate station transformers backed up by generation from two turbo-alternator sets, each set being supplied by steam from a different reactor. In addition, because the reactors are primarily to be regarded as heat sources which require to work at a steady temperature and, if possible, steady heat output, regardless of the generating variations which may occur, and because the Calder Hall reactors are primarily plutonium producers, full steam-dumping facilities have been provided so that the reactors may be maintained at full output even when no generation is taking place. This has meant the provision of two control systems, one for the reactor and one for the generated output.

The electricity supply system to the reactors is concerned with being able to maintain the control and cooling of the reactors, regardless of the fate of the turbo-alternators; and should the main supply completely fail at any time, an emergency supply must be available for the removal of the residual heat, for some ventilation, for the handling of active fuel during discharge and for the maintenance of instrument supplies.

The main station load, which constitutes about 17% of the generated output, is absorbed at the reactors mainly by the gas-circulator motors, and it has therefore been thought provident that the main station switchboards should be located at the reactors and not—as with a more orthodox station—in or near the turbine house. This has enabled the reactor to be treated as a self-contained unit for both its normal and its emergency supply (which is provided by a battery and back-up Diesel generators).

Another point which had to receive careful consideration was the rapidity of plant erection and commissioning to meet the programme and to provide an early supply for the circulator testing; until this had been provided, the circulator and its driving motor had not had a combined running test. This was greatly facilitated by the containment of services within the reactor building, and, in fact, the first turbo-alternator set commenced generation on the 27th August, 1956, just three years and three months after the opening up of the site, the station being officially opened and switched to the Grid on the 17th October, 1956, by Her Majesty the Queen.

(2) GENERAL DESCRIPTION

The station is located at Sellafield, on the North Cumberland coast, and is isolated to the extent that its main Grid connections comprise a single-circuit 132 kV line extending southwards 40 miles to Barrow and a double-circuit connection northwards 50 miles to Carlisle via Egremont and Stainburn. It is immediately adjacent to the Windscale plutonium factory, which provides a fairly considerable load, but apart from this there are few other loads of consequence in the vicinity.

The 'A' station as originally designed comprised two graphite-moderated carbon-dioxide-cooled thermal reactors and four turbo-alternators. Each reactor has four heat exchangers mounted externally to the building, the gas being circulated through these by four centrifugal-type circulators. Steam generated at the heat exchangers is passed to the turbine house, each reactor supplying steam at two separate pressures to the turbines, which are designed for h.p. steam at 200 lb/in^2, 590° F, and l.p. steam at 53 lb/in^2, 340° F. The generators have a continuous maximum rating of 23 MW and a power factor of 0·8, but at the moment are limited to 21 MW by the design figure for the turbine; the machines run at 3 000 r.p.m., the generated voltage being 11·5 kV. Two sets are used to supply the house load and export to the Grid, the other two sets being connected to the Windscale factory; again, any surplus generation is returned to the Grid.

The 'B' station is identical to the 'A' station so far as generation is concerned, the only difference being that, while two sets are connected directly with the house load as before, the other two sets export directly to the Grid.

Generated output from the machines can be varied without necessarily affecting the steam-raising conditions at the reactors,

Mr. Mackay and Mr. Hardwick are with the Industrial Group of the United Kingdom Atomic Energy Authority.

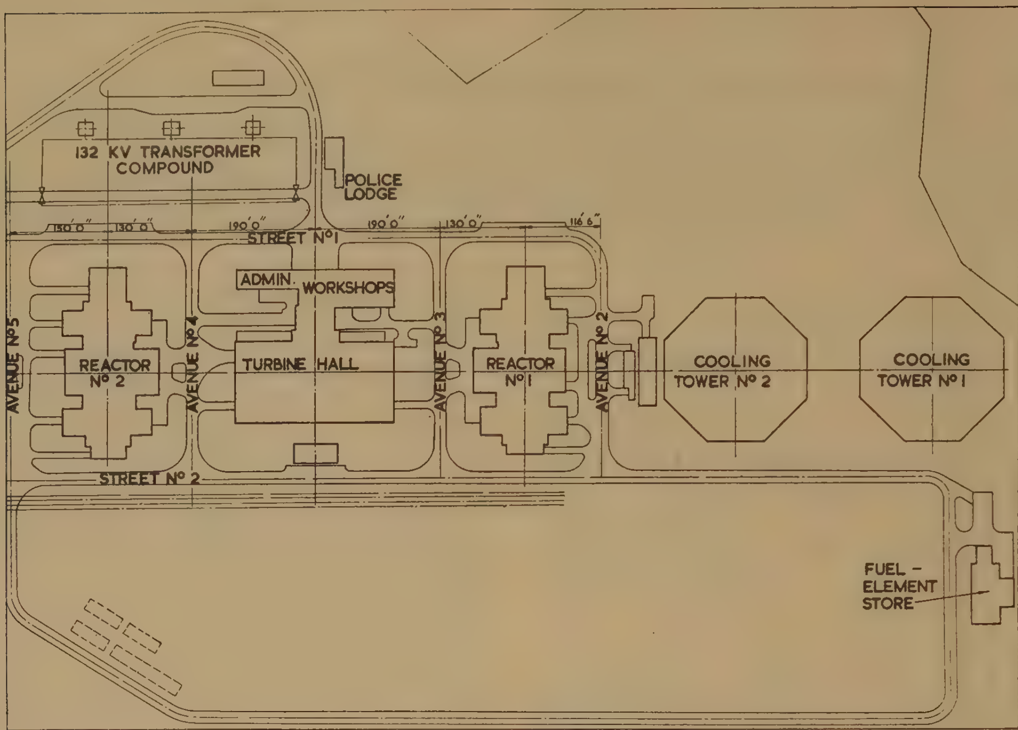


Fig. 1.—Calder 'A' site layout.

since dump condensers have been provided to absorb all the steam raised; this has created a rather special condition where the station auxiliaries can be nearly at full load with no generation taking place.

As shown in Fig. 1, the building layout has provided for a turbine hall, at each end of which, some 40 yd away, are the reactor buildings. The turbine hall is arranged to house the four turbo-alternator sets located transversely across the hall; and at 3 ft above the operating floor level, the 3·3 kV and 415 volt switchgear associated with the turbine auxiliaries is housed in a gallery extending the length of the building. Immediately below is a cable mezzanine in which are run the main generator and turbine-house supply cables. Below this are the transformer bays containing the house-service transformers.

The control block is built directly against the side of the turbine hall, and the electrical control room is on the same level as the turbine-house switchgear gallery. All buildings are steel framed and asbestos sheeted, apart from the h.v. switch and control rooms and transformer bays, which are constructed of brick. Sound insulation has been provided between the turbine hall and the control room and has proved quite effective in reducing the noise in the control room to an acceptable level.

The reactor building is essentially a concrete block, roughly 90 ft high × 60 ft square, surrounding the pressure vessel and core, on either side of which are built circulator houses, each containing two main gas circulators and their auxiliaries. The side facing the turbine hall is the control block, in which is located the reactor a.c. switchgear at ground level with the d.c. switchgear and batteries on the first floor. The reactor control room is immediately above with a cable mezzanine between the two floors. From here upwards are successively the burst-can detection equipment and the uranium fuel preparation room. On the opposite side to the control block is the discharge face of the reactor, through which are lowered the fuel elements taken from the pile-cap floor, through which all control, charge and discharge operations take place.

Water cooling is obtained by the use of natural-draught cooling towers designed to deal with the total steam produced from the reactors when the dump condensers are in use. An outdoor pumping station is located at the base of each pair of towers, the five driving motors contained in each being 600 h.p. 3·3 kV deluge-proof squirrel-cage units, horizontally mounted above the theoretical flood level and having in-built heaters to avoid condensation during standby periods.

General lighting throughout the station has been confined to the filament type of lamp, apart from the control rooms, where completely illuminated ceiling panels employing standard 5 ft fluorescent lamps have been used. Lighting fittings used in the turbine house and circulator houses are of the glass-reflector type permitting a degree of upward light to illuminate the ceilings. The emergency lighting scheme has been kept entirely separate from the main lighting.

(3) MAIN ELECTRICAL DISTRIBUTION

Fig. 2 shows that it has been possible, by virtue of the low rating of the alternators and by specifying for them a reactance of 15%, to switch directly at 11·5 kV, and apart from the Windscale feeds, to use switchgear of 500 MVA rating. Furthermore, by having the main circulator motors wound for this voltage, it has been possible to eliminate transformation losses and to guarantee their supply from the output of two alternators, each of which is fed with steam from a different reactor. In addition, parallel connection is maintained through the two 30 MVA transformers with the Grid, so guarding against failure of either the reactors or the 132 kV busbars.

The station is in no way self-starting, and therefore on start-up the equivalent of a paralleled station transformer supply is obtained.

The second pair of turbo-alternators at Calder 'A' is connected directly by 1 100 yd of cable to 750 MVA switchgear at the Windscale factory. Here the existing reactor cooling-air blowers are wound for 11 kV, and it was found to be more economical

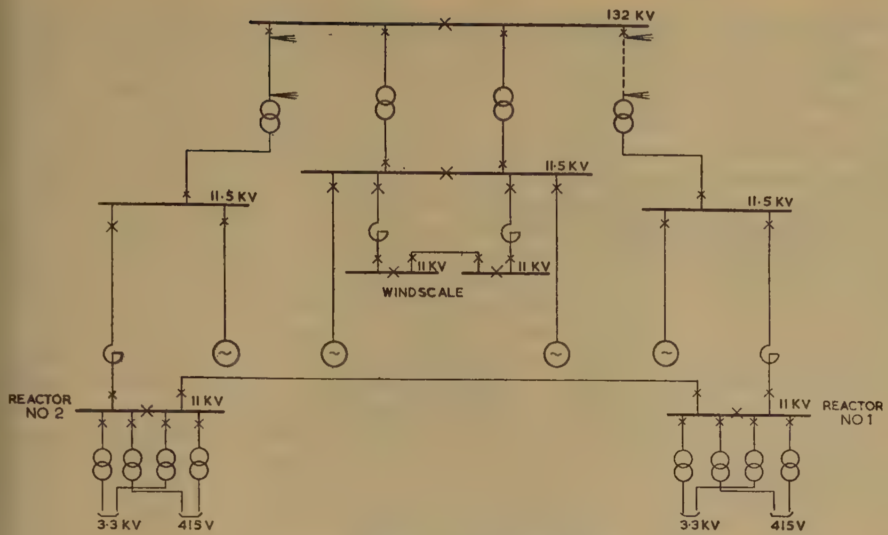


Fig. 2.—Calder 'A' h.v. connections.

to supply these direct by cable over this distance rather than use the double transformation involved in utilizing the 132 kV transmission lines between the two sites. The use of the larger switchgear occasioned by the introduction of the section switch enabling the two alternators and Grid transformers to be directly paralleled was considered necessary to minimize interference with the Windscale supplies while the extensive modifications were carried out, and to facilitate future extensions.

All alternators are connected to switchgear having an associated 11/132 kV 30 MVA transformer with on-load tap-change facilities. Main earthing of the 11 kV system is normally maintained through the earthing transformers associated with the 30 MVA Grid transformers. If, however, all Grid connections are lost, it is possible to select and earth one generator via a station earthing resistor rated to carry full-load current for one machine for 30 sec. High-impedance bus-zone protection with a check feature has been fitted to all 500 and 750 MVA 11 kV switchgear, and balanced protection on all major feeders and large transformers with back-up protection has been provided in all cases. The 11 kV switchgear of 350 MVA rating and above is of the oil-filled type, while the 3·3 kV 150 MVA and the 415 volt 31.5 MVA switchgear is of air-break pattern.

The reactor 11 kV boards are of the double-busbar on-load-selection type to give maximum flexibility and are electrical-reactor coupled to the generator boards to reduce their rating to 350 MVA.

The remainder of the house service a.c. supplies are by duplicate transformers run permanently in parallel at either 3·3 kV or 415 volts, the 3·3 kV supply being provided to cater for a number of turbine-house and pumping auxiliaries ranging from 110 to 600 h.p. Where duplicate supplies have been provided, physical separation has been carefully maintained by the use of separate subways and trenches, which in some cases are rather circuitous to maintain the separation. Cable subways have been used between the reactor buildings and the turbine house and have proved their worth in allowing constructional access around the reactor independent of the cable-laying programme.

It will be observed from Table 1 that the house load represents a considerably larger proportion of the total generation than with a normal coal fired station.

Table 1

Comparative House Loads for Nuclear and Coal-Fired Stations

	Calder 'A'	*Coal-fired station*
Number and size of sets, MW	4 × 23	4 × 30
Cooling-water circulation, MW	2	1·7
Turbine-house main auxiliaries, MW	1·3	1·9
Steam-raising plant ..	Reactors and heat exchangers, 10·2 MW	Boiler-house, coal and ash-handling plant, 3·1 MW

(4) STATION ELECTRICAL CONTROL

While each reactor has its own control room, these have no control of the electrical system, and this is provided at the moment in a central control room adjacent to the turbine house at Calder 'A'. When station 'B' is completed, the system will be controlled from there and change-over switches are being provided to effect this transfer. Local control can, however, always be returned to Calder 'A'. Centralized control of the main 132, 11 and 3·3 kV circuits has been arranged in this control room, all boards being of the normally-dark discrepancy type. The generator control board at Calder 'A', although arranged outwardly to display similar facilities for the control of all four sets, has, in fact, only two sets on local direct-wire control. The other two sets, which feed the Windscale factory, have their main switchgear 1 100 yd away at Windscale, together with a local control board, and all facilities are then brought back to the central control room via miniature-type equipment. Control of the reactor 11 kV switchgear is also brought back on miniature-type equipment, a local control board being located at each reactor in a room adjacent to the switchroom.

In order to maintain a uniform presentation and appearance in the control room, operation of the 3·3 kV switchgear has again been displayed on 6 in-wide miniature-type panels similar to the 11 kV ones, although the switchgear is itself located on the turbine-house gallery adjacent to the control block and could therefore have been a direct-wire system. In all cases the facilities for control and indication are retained at both local and remote positions by change-over switching, with the exception of governor and field control and indication for the two turbo-alternator sets supplying Windscale, where, because of the distance involved, emergency operation would have to be carried out by telephone instruction. Running controls only are provided at the control desk, running-up, circuit-breaker operation and synchronizing being carried out at the control panels.

The sets are normally running on steam-pressure control and can therefore accept some change in the steam conditions automatically. The governor, however, provides an overriding function, and since this has to be kept in step with the pressure control, a high and low setting alarm has been provided at the control panel to enable this adjustment to be watched.

Inter-tripping is provided on reactor shut-down with the generator circuit-breakers, since the steam conditions are such that it is considered dangerous to motor them from the busbars for more than a very brief period; this inter-tripping is obtained directly from the shut-down control-rod relays.

A reactor-fault alarm appears on the general alarms panel, and this is operated whenever the reactor 11 kV, 415- and 240-volt d.c. local alarm systems are energized to provide a 'night' alarm and supervisory check.

With the centralizing of control of all eight alternators in the Calder 'B' control room, the length of the control board has now increased to the extent that it has become difficult to read essential instruments from the desk position. Duplicate instruments of reduced size have therefore been added to the desk to indicate the active and reactive load, the main field current for all alternators and the tap-position indication of the Grid transformers, together with their corresponding controls. To enable control to be maintained at all stages of the operation of the reactors and consequent generation, an operational telephone system has been provided with the master station in the control room speaking directly to the turbine driver and also to each reactor control room.

(5) REACTOR ELECTRICAL SYSTEM

(5.1) General Distribution

The main reactor switchboard in each case is fed at 11 kV by dual feeds taken by separate routes, as previously explained, and the switchboard has been made of the double-busbar pattern for utmost flexibility. By treating the reactor as a unit, the cables for gas circulators and other important drives have been contained within the building, giving minimum lengths of cable and maximum security. The 11 kV switchboard, together with the main 415-volt distribution switchboard, has been located on the ground floor of the control side of the reactor, from which position duplicate feeders can be taken either via the basement and subways to the circulator houses or vertically to the pile cap. The emergency d.c. switchboard and battery, together with instrument and control-rod supply equipments, are housed immediately above, on the first floor, thus keeping all important connections as short as possible. The construction of a reactor comprising a central mass of concrete renders the electrical distribution difficult, and early thought had to be given to appropriate slots and cableways in the building structure, in order to provide connection between the various floors and faces. The general layout of the reactors is shown in Figs. 3 and 4.

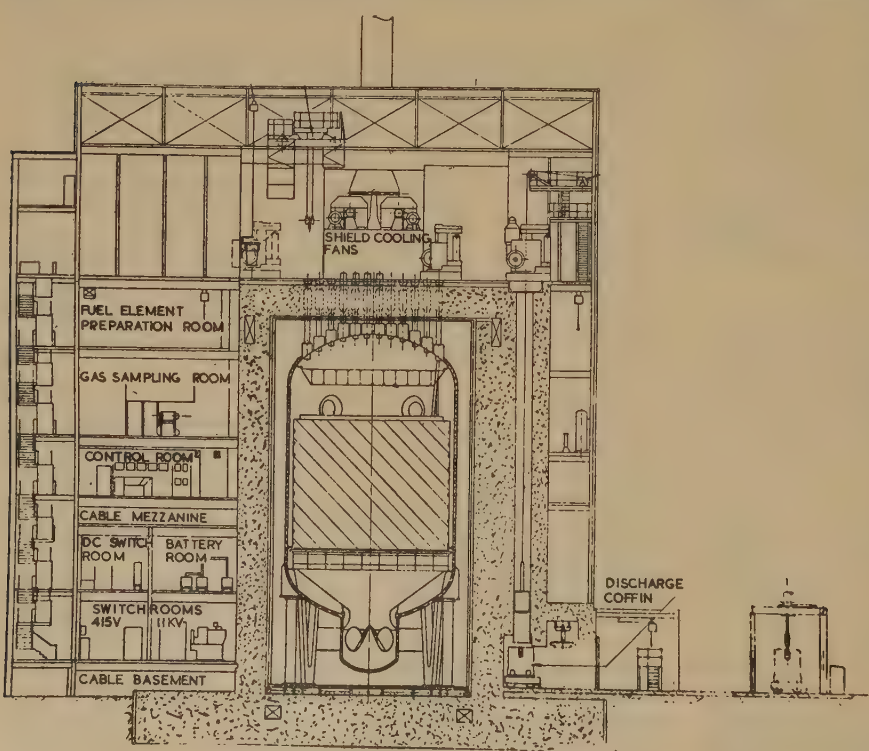


Fig. 3.—Section through reactor building.

Control of the reactor is centralized in a control room on the second floor, and control of the circulator speed and control rods is brought back to this position, together with a comprehensive alarm system. The majority of the equipment within the control room consists of instrument apparatus outside the scope of the paper, except to remark upon the large amount of instrument cabling in a project of this nature which must be segregated from the main power system to avoid pick-up. Vulcanized-rubber-insulated, single-wire-armoured and served multicore-type cables, with and without lead sheaths, were used for instrument connections to remote points; this work was then handled by the main installation contractor, together with the power cables, without the necessity for special treatment to avoid mechanical damage, especially during the construction period. Marshalling of cables necessitated the provision beneath the control room of a mezzanine floor in which junction boxes were located. Here the heavier cables are connected to the lighter-gauge wiring associated with the instrument panels above. The early construction of subways from the basement to the circulator houses permitted the installation of cables to proceed simultaneously with lifting of heat exchangers and other major constructional work.

The establishment of scrupulously clean conditions to permit the loading of graphite and for other work inside the completed pressure vessel resulted in the segregation of several of the control-face floors for a long period during construction. This had to be carefully integrated with the main installation programme and also required the setting-up of an air-conditioning plant and the use of the building lift at an early stage.

In order to accommodate a long programme of testing to prove the circulators and their gas circuits individually and collectively, together with testing the reactor proper, a permanent Grid supply was required at an earlier stage in the overall programme than is usual, with the result that the electrical installation proceeded with urgency, despite the fact that—as is often the case—the electrical requirements could not be cleared until a late stage in the design. Exceptional temporary measures were resorted to in several instances, in order to establish preliminary testing, e.g. the first circulator motor was turned over on a temporary 6·6 kV supply instead of the designed 11 kV, until the permanent supply could be made available. The requirement for circulator testing was therefore a target for the completion of the main electrical circuits. A detailed commissioning programme was prepared for the reactor plant, and testing schedules for all electrical equipment were drawn up to ensure that all functions were tested and that no interconnections between different sections of plant were overlooked.

A standard range of multicore cable sizes to be used was agreed at an early stage, with obvious advantages.

Great care was taken in achieving isolation arrangements for control boards, gauge boards and starters. This proved to be a serious problem, for example, in cases where controls for several different items of plant were grouped upon a common control panel, and has been solved in some cases only by the use of interposing relays at the plant being controlled, operated from a single supply at the control panel concerned.

The station has been clearly regarded as

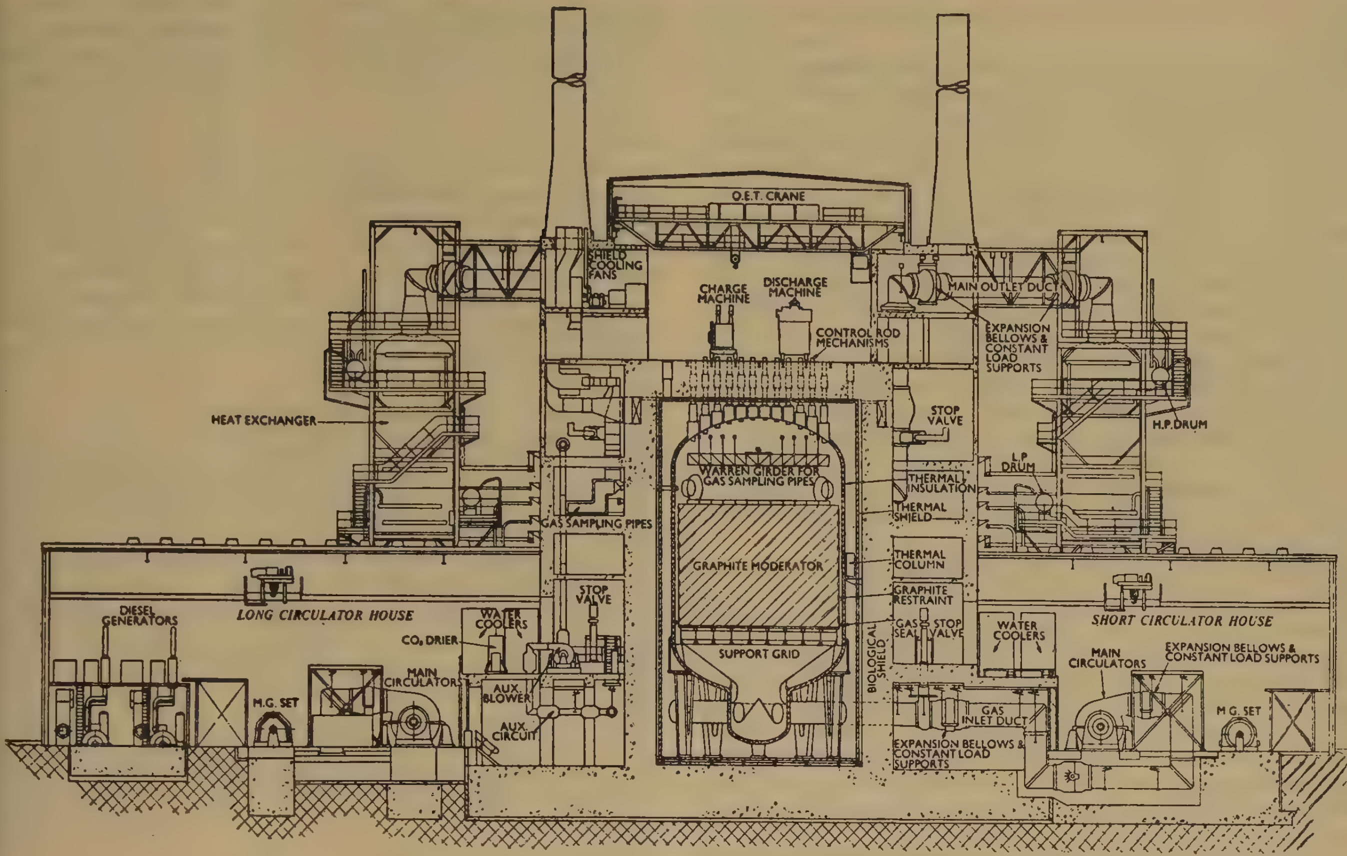


Fig. 4.—Section through circulator houses and reactor building.

coming within the scope of the Factories Act, and because the Authority must be able to transfer staff from its other factories, the safety aspect of the installation has been related to the Authority's general practice, e.g. all motor starters or circuit-breakers used for motor starting are fitted with a delayed under-voltage release feature.

The average running consumption of each reactor building, omitting the circulator load and battery charging, is approximately 0·6 MW. The circulator load may vary and is between 4 and 5 MW per reactor.

(5.2) Gas Circulators

There are four gas circulators per reactor, each associated with its own gas duct and heat-exchanger system. A variable speed range of 10 : 1 was specified for the circulator drive, in order to provide full flexibility for research and to permit close control of the start-up of the prototype reactor design. Since a proved and stable type of drive was required for this duty, the Ward Leonard system was selected for the purpose, after due consideration of a.c. variable-speed or rectifier-fed alternatives.

The main drive motor is rated at 2 200 h.p. when running at 940 r.p.m. with an armature voltage of 600 volts. The normal operating level is somewhat below this maximum rating, giving a margin of surplus capacity in hand for eventualities.

The Ward Leonard generator is driven by a 740 r.p.m. 2 500 b.h.p. squirrel-cage induction motor arranged to start direct-on-line from the 11 kV reactor switchboard and drawing a starting current limited to 3½ times full-load current. The generator is rated at 1 730 kW at 600 volts and is a separately excited shunt type with commutating poles and pole-face compensating windings. The design of the brush boxes permits the use of brushes in split pairs, and identical brush-gear arrangements have been made for both generator and motor. It has been impossible to arrange for on-load brush changing, and consequently facilities have been provided to enable single machines to be taken out of service for brush changing and other maintenance.

The speed of each individual drive can be set at any value down to one-tenth of full speed, and constant speed control at any setting is arranged by the use of a voltage regulator responsive to the armature voltage of the main motor, which is closely proportional to the speed. Movement of the regulator causes adjustment to the generator field in the appropriate direction, via a motor-driven potentiometer working on the field circuit of the respective exciter.

Each individual circulator may be operated under hand control from a local panel, or may be switched over to unified control from the reactor control room. The provision of local control permits full maintenance running facilities, so that individual machines can be taken out of service while the three others remain on 'ganged' operation. The machines are started and run up to a low speed under hand control at the local panel, and the speeds of all four circulators are then matched. They are subsequently switched over to adjustment from the reactor control room, where the four speed-setting resistors in the control-coil circuits of the regulators are ganged together to form a single handwheel type of control. The speeds of the four circulators are held approximately in step by the close regulation, so that there is no possibility of any reversal in gas flow taking place. A form of protection is fitted to detect faults in the regulator control circuit which may result in any individual blower not following the common controller, thus

getting out of step, and this operates an alarm in the control room.

Provision has been made on all the large machines for commutator grinding, and all machines have been fitted with heaters which are particularly useful during the erection and commissioning periods. The main machines are duct ventilated, drawing filtered air from outside and discharging this into the building. Special attention has been given to the amount of cooling air available under low-speed conditions of the circulator-drive motor, to prevent overheating of field coils, and the air ducts were treated in order to prevent cement dusting occurring.

A form of basement is arranged beneath each pair of circulator driving equipments and their auxiliaries, wherein all busbars, cables and pipework can be run. Here again it has been useful to marshal many of the control and interlock cables into junction boxes, to reduce the number of multicore cables which proceed to distant control points. Care has been taken to identify and ferrule the cores of all control cables in line with manufacturers' wiring diagrams, and numbering systems have been carefully scrutinized to enable equipments provided by different manufacturers to be properly integrated.

Starting-up of the a.c. motors, being carried out from the local control panel, necessitates the plant operators being 'partially authorized' for switchgear operation. A system of selector switches with key inserts ensures that control of the 11 kV circuit-breakers is available at the circulator control panel only at the discretion of the 'fully authorized' staff, who can, conversely, withdraw control of the circuit-breakers back to the switchgear control board for maintenance or other reasons. The removal of intertripping or main-trip circuit links at the switchgear has been arranged to cause operation of the circuit-breaker 'unhealthy trip' alarm lamp.

A system of earth-test voltmeters has been fitted to the local control panel, so that the busbars between the generator and the motor of each set can be checked at any time for earth faults, and this has proved useful in giving a rough indication of armature insulation resistance.

The design of the 4-ganged rheostat in the reactor control room has been considered to ensure that mechanical and temperature changes affect the resistors of all four circuits equally, to avoid the introduction of variations in the matched speeds. Since there is a continual heat loss of approximately 2·6 kW associated with the rheostat at top setting, care has been taken to ensure a robust, well-ventilated design.

The early proving of the circulator and its driving machinery has caused the Ward Leonard sets and the main motors to be run in conditions far from ideal with respect to the state of building construction. Great care is being taken to reduce the ingress of cement and other dust while construction is going on, particularly with regard to the commutator surfaces. Similar arrangements also apply to switchgear and control boards which have had to be installed at an early stage. Details of the form of shaft seal for the circulator drive shaft has been given elsewhere.* Since the shaft can be wound back onto a fixed seal, suitable interlocks have been inserted so that neither the main motor nor the pony motor can be started until this seal is cleared.

(5.3) Auxiliary Circulator Motors (Pony Motors)

Under conditions of reactor shut-down the accumulated radioactive products of previous fissions continue to produce heat, which must be removed. Since the loss of the main driving power to the circulators may be the cause of shut-down, it has been necessary to fit to each circulator drive a d.c. motor capable of running the drive at 10% of full speed. These d.c. motors are supplied from the reactor emergency system, and are arranged to start up automatically upon tripping of the associated a.c. circuit-breaker. A mechanical clutch is included in the drive, which engages when the circulator shaft has fallen to the correct speed. Each motor is rated at 15 b.h.p. continuously, but can produce a starting torque equivalent to 70 b.h.p. in order to be able to accelerate the circulator drive from rest if necessary. The motor is started by means of a multi-step back-e.m.f. contactor starter embodied in the circulator local control panel, and facilities are provided so that it can be hand started or stopped in addition to being automatically started. The automatic starting circuit has been made as simple and as secure as possible.

(5.4) Circulator Auxiliaries

Of these the most important are pumps for seal-oil and bearing lubricating-oil supply, since these oil supplies must be maintained whenever the circulator is running on main drive or on pony motor. Associated also with the oil circuits are water coolers, whose fans and water pumps must be similarly maintained. For seal and lubricating-oil circulation one a.c. and two d.c. pumps are provided, of which two sets, normally the a.c. pump and one of the d.c. pumps, are running at all times. Automatic starting has therefore been arranged for the standby d.c. pump and is initiated by detection of falling oil pressure. The water cooler drives are d.c. fed.

A comprehensive alarm system is provided for detection of abnormal conditions in the oil system and is arranged to indicate on the local machine panel. A single repeat of 'oil trouble' alarm is taken from each machine panel to the reactor control room.

(5.5) Protection and Trips Associated with Circulators

For maximum reliability, protection and other shut-down devices have been arranged to trip the 11 kV circuit-breaker associated with each machine, and, in turn, the tripping of these circuit-breakers has been used to initiate shut-down action elsewhere and to start the pony motor. In general terms, the reactor must be shut down in the event of failure of one or more circulators, because of loss of cooling and reversal of gas flow. It has thus been arranged that when any one circuit trips the remaining three are automatically intertripped. Similarly, the control-rod system is caused to carry out emergency shut-down action in the event of the failure of any circulator, and the pony motor is automatically started to remove shut-down heat. Should the control rod system shut down for any other reason, the circulators are, however, left undisturbed.

The protection of the a.c. motor of the Ward Leonard set is conventional, but includes time-delayed under-voltage protection. Among the individual trip initiations related to the circulator are overspeed, d.c. over-current, emergency stop and reversal of gas flow. To some extent the various trip arrangements mentioned are used to reinforce positively the instrument system, since the condition of the reactor is monitored at all times by various devices to prevent the occurrence of dangerous conditions.† These instrument devices act directly upon the control rod system.

There is an arrangement of interlocks to assist in the correct sequencing of circulator start-up, but the interlocks applied here and elsewhere do not relieve the plant operator of his responsibility, since over-reliance on automatic schemes may lead to a false sense of security. Much care has had to be taken

* BOWDEN, A. T., and MARTIN, G. H. 'The Design of Important Plant Items' *Journal of the British Nuclear Energy Conference*, 1957, 2, p. 161.

† ANDERSON, E., and BOWEN, J. H.: 'System Control and Protection', *Journal of the British Nuclear Energy Conference*, 1957, 2, p. 218.

in cases where conventional plant and switchgear has been used, because of the integrating of the general reactor conception of 'fail to safety' with the normal industrial practice that equipment must be energized to operate.

(5.6) Control Rod System

The requirement here was for the synchronized movement of a specified maximum number of control rods at selected speeds into and out of the pile, holding the rods stationary, or permitting them to fall under gravity in the event of power failure. The individual control-rod mechanisms were to utilize the same charge tubes that were used for charging the pile, and they were to withstand the effects of ambient temperature of 100° C and carbon-dioxide pressures of 100 lb/in². Each individual control rod has its own winch mechanism and is driven by a synchronous motor having a 3-phase stator and unwound variable-reluctance rotor. Each motor is capable of locking into step with supply frequencies of 0·0133 c/s (slow out), 0·133 c/s (normal in), 1·33 c/s (fast in) or 0 c/s (held stationary). Class-H insulation is used, and since each machine is pressurized with carbon-dioxide at the reactor operating pressure, the electrical leads, together with those for instrument connections, are brought out through a pressure-sealed terminal box.

The variable-frequency supply is obtained from a rotating frequency-convertor set with a second set as standby, and is fully equipped with change-over facilities, duplicated contactor circuits and mechanical and electrical interlocking, in order that no incorrect sequences can take place. All circuits are arranged to fail to safety. The frequency-convertor sets are located on the first floor of the control side, with controls and contactor equipment on the second floor, from which point individual feeds are taken up the control face to the pile cap.

The number of charge tubes on the pile cap is 112, of which a selected 72 were originally considered as possible control-rod stations. The precise number and pattern could be determined only by practice and has only recently been confirmed. Thus the distribution system was arranged for 72 stations, and therefore provides some flexibility in the choice of control-rod position.

The problem of distribution on the pile-cap floor was solved by the use of floor ducts, and here, owing to space restrictions and high temperatures, use was made of mineral-insulated cable. The distribution cables are each terminated in a special junction box adjacent to each mechanism, so that flexible cables can be connected to the machine terminals, thus permitting ready disconnection to take place when the mechanisms have to be removed for charging purposes. Simple means are provided in the junction box to prevent the connections being replaced in the wrong order.

A small number of mechanisms may be selected from the total and connected to a separate potentiometer system for trimming control. The current taken by each control-rod motor is approximately 5 amp at 40 volts r.m.s., and the frequency convertor sets are driven by 37·5 b.h.p. squirrel-cage motors capable of running continuously on voltages down to 50% of normal. The main supply to these two motors is taken from opposite sides of the main 415-volt switchboard, and the fail-to-safety features embodied safeguard the reactor in the event of complete loss of supply. All control sequences are arranged to operate from a 50-volt d.c. battery-maintained system, so that local supply failures will not trip the pile needlessly.

Incorporated into the control system are shut-down relays upon which operate the general safety instrumentation of the reactor, and the rods can, by this means, be lowered in for safety reasons. Such a shut-down would in turn initiate the tripping of the main turbo-alternator sets to prevent motoring through loss of steam.

Arrangements are made to permit the standby frequency-convertor set to be tested against a dummy load, so that when maintenance has been carried out it is not necessary to connect the machine to a live load to prove its operation.

(5.7) Charge and Discharge Equipment

The reactor has been arranged for off-load charging and discharging, and consequently the supplies to the appropriate handling plant are largely non-essential. The possibility of a mains failure occurring during a partly completed discharge cycle has been considered, however, since under these conditions it is very necessary to be able to dispose of the highly active elements removed from the pile. Means are therefore provided so that a limited number of drives, including ventilation, may be operated via a motor-alternator set driven from the d.c. system. Change-over to this supply is carried out manually.

While the mechanical-handling plant concerned is extremely novel in feature, including both hydraulic and direct drives, the machines are equipped with conventional-type electrical equipment of robust design. Here, as elsewhere, it is considered that, because of the large problems being tackled on the mechanical side, it must be possible to place reliance on the conventional electrical plant. As one aspect of this, every endeavour was made to reduce the number of limit and interlock switches to a minimum and to ensure that they were of robust design.

The charging and discharging of elements is effected down the same charge tubes that house the control-rod mechanisms, thus necessitating the removal of the latter at each shut-down period for recharging. The area is served by an overhead crane capable of extremely precise location over the charge holes and embodying Ward Leonard drives to all motions. The charge and discharge machines are fully mobile and capable of travelling on any of several sets of rails embodied in the pile-cap floor. They are therefore fitted with flexible cables, contained in carefully positioned reeling drums on the machines and capable of being plugged into appropriate fixed sockets. These flexible cables are heavy-duty earth-screened type, and as an added precaution all machines rails are bonded to earth.

A further example of the necessity to use flexible cable occurs for the grab, which is lowered into the charge tubes. The grab is electrically powered and is used to place and extract the fuel elements. It was most convenient to design a single cable embodying a wire rope to support the grab together with the electrical control connections. A special cable was laid up for the purpose, comprising a stainless-steel core wound with six nickel-plated-copper p.t.f.e.-insulated wires, sheathed by silicone rubber and braided with Terylene, capable of withstanding high temperatures and irradiation effects from within the pile.

Where the fuel elements are lowered from the pile cap and collected in a 'coffin' for transport to the Windscale factory for treatment, conditions of high radiation and contamination exist. Here the electrical equipment has been located away from the active zones, and the installation is generally concealed beneath the wall surfaces or otherwise arranged to permit hosing down to remove contamination.

The pile cap is the sole access face for the completed reactor, and installation facilities must be provided for various measurement, research or viewing devices to be inserted via the charge tubes. For instance, the placing of fuel elements carrying thermocouples necessitates special indicating arrangements. It is also possible to lower into the charge tube a closed-loop television camera with a diameter of 3½ inches and carrying its own illumination.

(5.8) Gas Valves

Wedge-gate valves have been used in the main duct system to close off each main gas duct. Automatic operation of these gas valves to prevent reversal of gas flow consequent upon circulator failure has not been included, because of the inherent danger that some fault may cause simultaneous shutting off of all gas ducts and thus lead to dangerous conditions in the reactor. For security reasons the gas valves have been arranged to operate from the reactor d.c. emergency system, and their control is conventional. These valves take some 3 min to travel through their full range.

(5.9) Instrument Supplies

An essential instrument load of 12 kVA at 110 volts a.c. must be supplied whether the pile is running or not, and thus arrangements have been made to feed this from a motor-alternator set driven from the d.c. system. This set is complete with 100% standby and has both voltage and frequency regulators to enable the voltage to be maintained to within $\pm 1\frac{1}{2}\%$ of setting irrespective of supply and load fluctuations and frequency to be maintained within $\pm 1\%$. Since it was thought that bringing the standby machine into service might inadvertently cause disturbance of the supply, an automatic change-over device is also included, whereby in the event of a transient drop in voltage, the instrument load is changed over to a transformer-fed supply. Care has been taken in designing the change-over device that no paralleling of the transformer and motor-alternator supplies can take place, and a minimum time of 200 millisec has been achieved for this on-load change-over. All instruments are adapted to permit this break in supply without tripping the pile.

(5.10) Remainder of Reactor Auxiliaries

Each heat-exchanger is complete with a pump house at its basement having conventional-type normal running and standby a.c. pumping equipment. Since the heat-exchangers are outdoor structures, it has been necessary to apply electrical trace heating to certain pipes, especially those which lead to instrument devices, and also to provide local heating for these devices, to prevent freezing in extreme conditions.

An essential extraction ventilation system driven by 120 b.h.p. a.c. motors is installed in the reactor to ventilate the space between the pressure vessel and its biological shield. This also permits the cooling of the operating floor at the pile-cap level. A 50 b.h.p. d.c. standby machine is arranged for these fans to maintain this cooling under emergency shut-down conditions.

A complex installation is provided for the detection of burst fuel-element cans within the reactor, necessitating the operating of a number of valve and precipitator f.h.p. motors on a continuous cycle of 5 sec on and 25 sec off indefinitely, and appropriate contactor equipment has been installed. While the remainder of this equipment is largely of instrument nature, the problem for the electrical designer is to achieve a satisfactory route for electrical and instrument cables among the mass of piping and ductwork involved. Other drives within the reactor building are up to 120 b.h.p., but many are of intermittent duty and all are conventional. They are supplied from the 415-volt a.c. distribution system.

(5.11) Miscellaneous

Among the minor points which may be noted is the necessity to ensure that contaminating materials may not penetrate the reactor vessel by means of the charge-tube holes at the pile cap. Thus in this vicinity the use of lead-base paint has been restricted, and no devices containing mercury are tolerated in any electrical equipment. A close check was made on the possibility of emission of contaminating substances from electrical equipment in the area.

For all important motor drives, starters of the latched-in pattern have been used, embodying a tripping circuit working from 50-volt battery supply. Standby electric motors have generally been fitted with bearings of the sleeve type, with the object of avoiding indentation of ball bearings caused by long periods of idleness under conditions of vibration. Heaters have also been fitted to prevent condensation.

As a general practice, all cables within the building are served with fire-resisting material, and care has been taken to seal the various cable slots between floors. A fire-alarm system has been installed because of the large number of floors involved.

A comprehensive earthing system is included within the building, and is connected to a system of iron pipes in the vicinity of the reactor building. Since these have been in part installed in back-fill, the earth plates have in turn been interconnected to the remainder of the station earth system and have produced a satisfactorily low earth-plate resistance, even though the general soil material is of poor quality.

In several instances the siting of electrical equipment and control panels has had to be considered in relation to the calculated radiation hazard which might exist. The plant has subsequently been the subject of careful checking in this respect, and in one or two instances additional shielding has been added. The construction of heavy shielding walls is a difficulty to be overcome by the installation designer when considering the siting and cabling of electrical gear. Suitably disposed socket-outlets have been installed within the reactor for the operation of welding sets, radiation monitors and other instrument devices, commutator grinders, bolt-heating transformers, vacuum cleaners and man-cooler fans, all of which may be required at some stage of the plant operation.

(6) REACTOR EMERGENCY SUPPLY

Because heat removal from the reactor must be continued for some time after the initial shut-down and failure to do this would cause very considerable damage, a separate emergency supply has been provided for each reactor and an entirely d.c. scheme has been adopted for this supply, with the exception of 12 kVA of instrumentation load for which there was no alternative. This was thought to be preferable, since it eliminated converting plant between the battery as the immediate source of emergency power and the driving unit. This principle has been adhered to throughout the plant.

The arrangement of supply, as shown in Fig. 5, has provided for a 1950 Ah 240-volt battery floating on d.c. busbars normally supplied from a 400 kW rectifier connected to the reactor main a.c. system. This supplies a continuously running d.c. load, and should the a.c. supply fail, either because of a general failure or a local rectifier fault, the battery continues to carry the load, for which it has an estimated capacity of 30 min, until the two 500 kW Diesel generators, which are automatically started on a.c. supply failure, run up and the preselected machine closes on to the d.c. busbars.

The d.c. switchboard provided is of cubicle type with a 'dead front', and all circuit-breakers are rated to deal with a potential fault current of 55 kA, which provides for parallel connection of the rectifier, battery and Diesel generator. Because of the size of the d.c. battery, no end-cell switching has been provided, and consequently there is a voltage variation of 210-330 volts on discharge to gassing-charge conditions. This, however, has been catered for by the motor manufacturers, and machines have been provided having not more than 10% speed variation

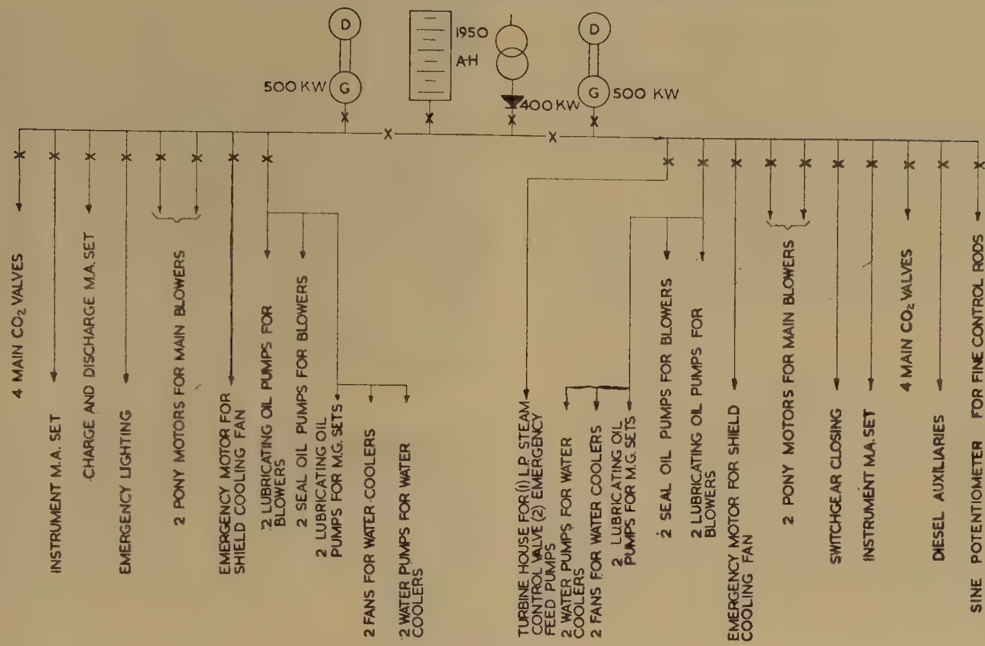


Fig. 5.—Gauranteed d.c. supply system.

over this range of voltage. No change-over switching has been necessary on the scheme provided, and since the only connection to the normal running supply is via the rectifier, which cannot reverse the power flow, it is considered that possible disturbance to the system on transition from normal to emergency conditions would be a minimum.

Because the wide voltage range (rising to 330 volts) can be reproduced under emergency conditions by boost charging from the Diesel generators, the emergency lighting system must be arranged to accommodate this. Stabilizer devices have therefore been fitted, which are capable of inserting series resistance in a suitable number of steps as the voltage rises, utilizing voltage-sensitive relays and contactor equipment.

Automatic starting-up of the Diesel engines is initiated by the dropping out of the rectifier circuit-breaker, and a fail-to-safety feature is embodied by arranging the starting air solenoid to be de-energized for starting-up. Although two Diesel engines are generally started up on initiation of supply failure, the automatic closing circuit of only one machine is put into operation. This automatic circuit adjusts the voltage of the incoming machine to equal that of the busbars, and then closes the circuit-breaker. This prevents any further deterioration in the busbar voltage caused by battery drain, and the machine may be loaded up by field adjustment; the spare machine may then be shut down when the immediate alarm period has passed, as convenient.

An alarm and indication system is taken back to the reactor control room to warn the operator in the event of the loss of the rectifier not being followed by the switching-in of a Diesel generator. The opening of the battery circuit-breaker also initiates an alarm. The battery circuit is protected by an instantaneous high-set over-current relay device only.

The time taken from the initiation of start-up to the generator being connected to the busbars is 75–90 sec, but frequent testing has proved necessary to ensure that operation is not nullified by failure of some minor component to function correctly.

(7) STRESS RELIEF OF PRESSURE VESSEL

Although not part of the final installation, a brief description of the electrical work involved is included here in view of the somewhat unique requirement. It was decided that it would be necessary to heat the main pressure vessel (which is approximately 70 ft high and 40 ft in diameter with walls 2 in thick) to 600° C and to maintain it at this temperature for several hours, in order to relieve the stresses resulting from the welding of the sections of the vessel. Electric heating was chosen as the method to be used, and a design was called for which would operate from the 415-volt supply and be within the capacity of the site construction supply transformers, namely 1 500 kVA.

The design chosen was to form a heater consisting of a cage of stainless-steel tubes built up inside the pressure vessel, supported and insulated from it. The steel tubes were arranged as two separate elements, each being a star-connected arrangement with approximately 90 yd of stainless-steel tube per phase. There was one current path per phase only, i.e. 90 yd of stainless-steel tube between each terminal and star point. The heater material used was stainless steel of welding quality supplied in random lengths and jointed by welding. For the main element, 2 in o.d. (nominal) and 0·109 in wall thickness was specified, and for the control element 2 in o.d. (nominal) and 0·093 in wall thickness tube was used.

The insulating materials used were solid quartz, woven quartz-fibre cloth and asbestos tape. The heater was supported from the dome of the pressure vessel and allowed to hang freely, turning inward at the base of the vessel so that expansion of the element could be taken at the knuckle so formed. The ends of the stainless-steel tube were welded at the bottom of the vessel to terminal pieces formed of solid round steel bar, and were brought out at the bottom gas-circulating ducts for connection to the controlling switchgear. The heater was built up without insulators, which were added subsequently. When completed, all insulators were carefully cleaned to free them of considerable amounts of loose scale and rust, and the final checks indicated an insulation resistance of 0·5 megohm.

Owing to the increase of the resistance of the stainless-steel tube when brought up to its operating temperature—approximately one-third of its original value—the elements were designed to absorb the 1 500 kVA fully when hot; and in order to minimize the starting-up overload, one element was switched in first and allowed to come up to temperature before the second was

switched in. Inspection of the heater subsequent to its use showed no appreciable deterioration of either the element or the insulation. A considerable amount of scale was present on the walls, and there were rust particles on the insulators at the bottom of the pressure vessel. The vessel took about two days to come up to temperature, at which time all heating was switched off, and it took about two days to cool.

For the stress relief of the heat-exchangers, which were delivered in sections and welded on site, local heating was preferred, and this was carried out by induction methods at 2·5 kc/s. To facilitate the progress of this work a system of busbar distribution and flexible cable coils was employed.

(8) CONCLUSIONS

Insufficient time has elapsed to draw any firm conclusions as to the behaviour of the installation under full operating conditions, except to record that the provision of the duplicated supplies to each reactor has been valuable in cases where fault tripping has taken out one of the feeders. Similarly, the change-over from the 'A' to 'B' stations of the main control, together with the expansion of the Grid system to accommodate the Calder 'B' extension, has been greatly facilitated by the duplication of supplies, which has enabled work to proceed without loss of generation.

Experience has shown that the provision of subways around the reactor has permitted the rapid installation of cables simultaneously with erection of large items of reactor plant, and has obviated the necessity of very awkward runs to avoid the main shielding. The large volume of control and instrument cabling approaching the centralized reactor control room has indicated that an increase in size of the cable mezzanine would have been desirable. Similarly, the circulator houses also provided a cabling problem arising from insufficient space. For future stations where combined electrical and reactor control rooms may be considered the magnitude of the cabling problem should not be underestimated.

(9) ACKNOWLEDGMENT

The authors wish to record their thanks to Sir Leonard Owen, Managing Director of the U.K.A.E.A., Industrial Group, for permission to publish the paper. They also acknowledge the assistance rendered by Mr. P. T. Fletcher in the preparation of the paper, and the contribution rendered by the C.E.G.B., North Western Division, in the solution of problems associated with the connection of the Calder Hall station to the Grid system.

DISCUSSION ON THE ABOVE PAPER

Before a meeting of the UTILIZATION SECTION *held in conjunction with the* BRITISH NUCLEAR ENERGY CONFERENCE 15*th January, before the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH 6*th January, and before the* NORTH MIDLAND UTILIZATION GROUP *at* LEEDS 17*th February*, 1959.

Mr. A. T. Crawford: The paper records the electrical aspect of a power station which presented entirely new problems; since it refers to the initial installation at Calder Hall 'A' site, its scope is necessarily limited, and I hope that further information will be forthcoming on the current position and operational experience in its electrical aspects. Much of the scheme outlined represents good practice, and any variation would seem to fall within the realm of personal opinion.

Two control rooms are provided, one for the adjacent nuclear reactor and the other for the generators and associated electrical system; such segregation has not been adopted for the C.E.G.B. stations, and the authors' views on the desirability of segregating these controls from the operational point of view would be useful. They have established quite conclusively that siting the nuclear-reactor control room adjacent to the biological shield gives advantages in respect to the cabling and commissioning involved.

Fig. 2 refers to both nuclear and electrical reactors without distinction. Since the electrical engineer's first concept of a reactor is a current-limiting device rather than the nuclear one, it might have been wiser to discriminate. The diagram could also be amplified to show the normal running connections of the network, i.e. whether or not all section switches are run closed, and whether the interconnectors between the two 11 kV boards at Windscale and the reactor 11 kV boards at Calder Hall 'A' are solidly connected.

In referring to the earthing arrangement adopted for the 11 kV system the authors state that if all Grid connections are lost, i.e. the four 30 MVA transformers, it is possible to select and earth one generator through the station earthing resistor. This is not quite the position because, with four 30 MVA transformers disconnected, two separate 11 kV networks exist, and I believe that each pair of generators has been provided with selective earthing facilities and two generator earths must be applied. The main nuclear-reactor switchboards, Nos. 1 and 2, are fed primarily through the electrical reactors from generators 1 and 4 and the dual feed mentioned is presumably the interconnection between these two boards. Presumably the flexibility conferred by duplicate busbar-pattern switchgear is the facility for restoring normal system connections in the event of any busbar fault, since with the busbar-zone protection one could anticipate a minimum of physical damage in the event of such a fault.

I agree that the adoption of a standard range of multicore cable sizes is of considerable benefit and facilitates the planning of the system. With a large battery provided for the nuclear-reactor emergency supply, the authors rightly draw attention to the voltage which can be experienced on the d.c. system, and refer to the necessary steps to safeguard the emergency lighting system. This aspect must also be borne in mind when considering the d.c. supplies for switchgear, since the closing coils for magnetically operated circuit-breakers are normally specified to operate within a range of 80–100% of the normal battery voltage. The nature of the circuit-breaker mechanism is such that accurate dashpotting must be provided during a relatively short travel at the end of the stroke; any large increase in operating voltage would tend to give overtravel and could well permit excessive mechanical stresses to be set up.

Some reference is made to the centralizing of control in the Calder 'B' control room with change-over switches in the Calder Hall 'A' control room to effect transfer of the control point. Ganged slider-type switches of a very robust pattern have been used for this purpose, such as were developed for use immediately prior to the war when it was customary to provide two or more control points in the power stations then being built. The investigation of the circuit details to achieve the duplication of control was quite considerable. So far as I am aware, the changes involved at Calder 'A' were carried out without interference to the normal running of the plant.

One can have considerable sympathy with the authors in that the electrical requirements could not be cleared until a late stage in the design, but this condition is really pertinent to the majority

of nuclear development work by virtue of its novelty, and it says much for the teamwork of all the interested parties that very tight installation dates have been maintained.

Mr. J. E. Makin: The reactor and generation control systems at Calder, which is primarily a plutonium plant, may be independent of one another, owing to the inclusion of 100% dump condenser capacity. In the civil stations, where electricity production is pre-eminent and the reactors are considered merely as part of the steam-raising plant, these systems are intimately related and the reactor must follow, preferably automatically, changing load demands. Thus, one central control is envisaged for the running control of all main plant items, rather than separate reactor and generation control centres.

The selection of the method of blower drive is of paramount importance. The authors mention three possibilities, but with the larger-capacity blowers required in the civil stations, such methods as a constant-speed induction motor with speed variation by means of hydraulic coupling, the use of variable-frequency turbo-alternators supplying groups of blowers, and direct steam-turbine drive, must also be considered. At a base-load station, machines employing brushgear must, if possible, employ on-load brush-changing techniques.

The selection of the optimum emergency-supply system has given rise recently to much controversy. Three methods are possible; the pure d.c. system as at Calder; a system utilizing all a.c. auxiliaries, non-interruptable services being initially fed from batteries via convertor plant, the remainder from Diesel alternators; or a hybrid scheme where the first-category auxiliaries are fed direct from batteries and the second from Diesel alternators which back up the batteries through rectifier plant. Many factors influence the choice, not the least being reliability. The introduction of rectifier or convertor plant, in many engineers' views, reduces the reliability. It appears that the Calder Hall and Chapel Cross pure-d.c. systems are difficult to refute.

Mr. E. W. Connon: The scheme adopted for the Grid connection was greatly influenced by the fact that a switching station already existed at Windscale when Calder Hall was first proposed. As a result, it was more economic to extend this station than to create another one at Calder Hall, which is only about 1 000 yd away. This fact, of course, greatly simplified the arrangement whereby the generators are connected to the Windscale 11 kV busbars to back up the supply to Windscale.

Fig. A shows the Grid system in the area surrounding Calder Hall and the connections of the generators at Calder 'A' and 'B'. As the authors have pointed out, there are no loads of any magnitude in the area, other than the Windscale one, and the introduction of a substantial block of generation in such a place has had considerable effect on the system since the station was built. There is a fairly modern station at Roosecote, the official opening of which took place only 18 months before that of Calder Hall, and which has been somewhat limited in its subsequent use. The introduction of large blocks of generation in the area by the connection of both Chapel Cross and Calder Hall, to the Supergrid at a point near Carlisle has necessitated the construction of a 275 kV line from there to Penwortham. This shows how the activities of the U.K.A.E.A. in producing large blocks of power in one part of the country and absorbing large blocks in another gives the transmission engineer plenty of work to do. The fact that these two stations were not designed as an integral part of the supply system has meant that the transmission arrangements, including this 275 kV line, are perhaps unduly expensive.

Finally, I should like to refer to the arrangement described in Section 4 of the paper, whereby inter-tripping is provided on reactor shut-down with the generator circuit-breakers. This is not the normal practice in conventional stations, and at Calder 'B' it seems that it has already contributed to a quite

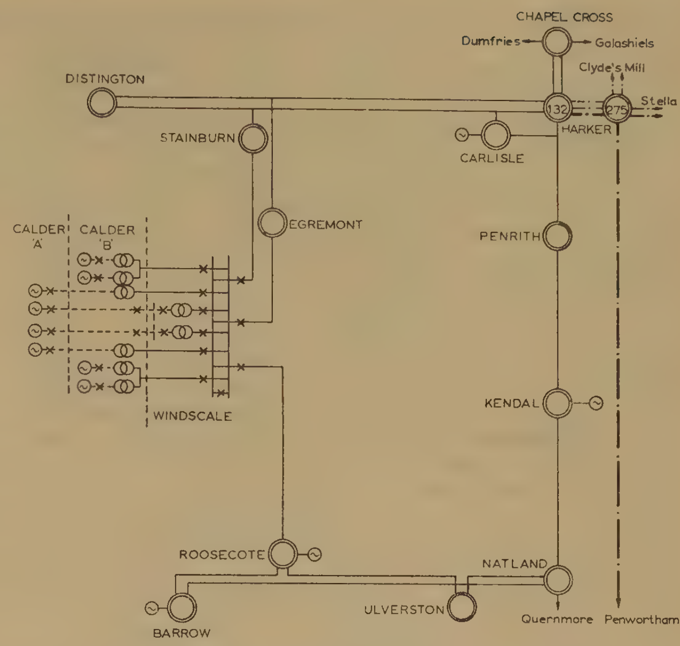


Fig. A.—Authorized system connections from Calder Hall.

— — — 11 kV.
——— 132 kV.
— · — 275 kV.

considerable disaster. The art of protective-gear application is very much one of compromise, in that in giving protection against one possibility there may be the introduction of risks in other circumstances. I should like the authors' comments on the dangers of motoring the generators, against which they were trying to provide protection, and on whether they still think that these dangers are greater than that which has already been realized at Calder 'B'.

Mr. R. Ball: In commenting on this paper it must be remembered that there have been considerable advances in reactor technology since Calder Hall was designed. Moreover, for civil stations, the economies of design are framed entirely to produce electricity at an economic price, consistent with safety. Furthermore, it is desirable to build more reliability into the electrical system than for a coal-fired station, owing to the inherent slow recovery of a nuclear reactor to full load after a shut-down.

It is of interest to compare the station load of 17% generated output at Calder Hall with that of Hinkley point, where the comparable figure is approximately 14%. The variation is probably due to the greater size of the latter. A typical figure for a conventional station would be about 7%.

I believe that at Calder Hall there has been a certain amount of pick-up between the earthing system and the instrumentation cabling. Could the authors give further information on this, in view of the possible serious effects on the reactor instrumentation?

In Fig. 5 it is noted that two Diesel generators are used with a rectifier in parallel. Three criteria have been now laid down for electrical system design in a nuclear station as follows. First, no two simultaneous or unrelated faults must endanger the reactor. Secondly, at the time of fault, one of the reactors in a 2-reactor station may be shut down for maintenance (at Calder Hall this would also apply to refuelling). Thirdly, in establishing reactor safety, no reliance shall be placed on electrical supplies external to the station. Since one Diesel engine could be undergoing maintenance at the time of fault, to what extent do the authors believe that their scheme meets these conditions?

The emergency battery at Calder Hall has a 30 min rating, which seems to be very pessimistic. Has this been justified by operating experience? The paper states that frequent Diesel testing has proved necessary to ensure that faulty operation is not caused by the failure of some minor component. Does this refer to the Diesel engines or to the automatic starting equipment?

Mr. J. Tozer: The planning of the cable installation must have been made very difficult by the lack of detailed information, particularly on control, during the early stages of the programme. Fig. 3 shows the d.c. switchroom immediately above the 415-volt switchroom; cabling to the former must have been very difficult unless the cables were run under the ceiling of the latter. The practice of marshalling the cables to the control room using junction boxes for the connection of cores of the v.r. cables to lighter-gauge wiring associated with the panels was presumably due to lack of space in the panels. This practice necessitates an additional joint or connection per core and must be a possible cause of trouble or error.

I understand that one 50-volt battery is provided for both the tripping supplies and all alarm and telecommunication duties for one reactor. Since the alarm and telecommunication circuits are often very complex and usually spread in quite vulnerable positions, it is common practice to provide a battery for these duties and an entirely separate battery for tripping supplies.

It is noted that some of the more important motors are equipped with heaters to prevent dampness occurring when the motors are off load. Care should be taken to prevent any moisture being driven out of the motor casing into the terminal chamber and causing trouble there.

On-load brush changing for the Ward Leonard sets is stated to have been impossible to arrange, but this facility is now being offered for slip-rings and exciters for alternators up to 200 MW. Could not similar methods be used for the Ward Leonard machines?

The large voltage range on the emergency-supply scheme may introduce trouble on contactors owing to contact bounce at the higher voltage, which could lead to the welding of contacts.

Mr. E. Anderson: The authors describe a d.c. system of guaranteed electrical supplies which is simple and straightforward but rather clumsy. It is well known that d.c. motors are much larger and more costly than their a.c. counterparts, but in the system described these motors must cope with a voltage variation from 210 to 330 volts. This means that the machines are particularly large and expensive.

The embarrassment which this caused in the Calder Hall project, and other obvious reasons, led the group with which I am associated to investigate a guaranteed a.c. system in which the drive of the a.c. motors is obtained through motor-alternator sets from the batteries. Quick-starting Diesel engines are used to pick up the long-term load. We promptly experienced all sorts of design difficulties, and found that we had transferred most of our problems from the d.c. motors to the motor-alternator sets. In particular, there were problems associated with the reversal of the current flowing through the motor-alternator sets and the sudden picking up of load. Development of a.c. systems has advanced, and I believe that the a.c. system is now in a satisfactory form; we feel that it can be made reasonably straightforward and are continuing to use it. In retrospect, knowing the time and effort taken in developing a.c. systems, I believe that the decision to use a d.c. system at Calder Hall was the right one, in that it conserved technical effort in a very tight programme. All guaranteed systems now seem to resort to the use of quick-starting Diesel sets, and I should like the authors to indicate their experience with these over the last two years.

Mr. D. J. E. Evans: Some time ago we had occasion to study variable-speed drives for gas circulators in nuclear generating stations. When considering commutator machines it is important to assess the brush life. For d.c. machines we approached several users of large equipments, and after many discussions concluded that it was reasonable to expect a brush life of six months with machines of a rating similar to those at Calder Hall. Another conclusion was that one should not be unduly surprised if a brush life of only three months is achieved in practice. Would the authors agree that our forecast of about six months was optimistic? It was difficult to obtain detail factual information on brush life. Work is proceeding in the academic world on the fundamentals of commutation, and it will be necessary to correlate this with experience in practice. Because of this need and the relatively large number of such machines at Calder Hall and Chapel Cross, it would be of particular value if detailed records were kept of d.c. machine behaviour. Are such records now being kept? It is of interest to note that, in a report prepared from information supplied by some twelve British generating stations, it is stated that brush life of at least a year can be obtained on a.c. commutator motors used for such duties as induced- and forced-draught fans, exhausters and circulating-water pumps.

The authors state that early proving of the circulator and driving machinery is necessary. In view of the importance of the gas-circulator drive, were any special tests instituted on the d.c. machines during inspection and testing at the manufacturer's works? Finally, what has been the experience with the brushes on the frequency-convertor sets used for the variable-frequency supply for the control rods?

Mr. G. C. Allingham: Special circuits are shown for supplies from Calder Hall to Windscale; but are not the Windscale reactors being shut down? The first reactor, of course, was destroyed, and I understood that it had been decided to shut down the second. We are told that an advanced type of reactor is to be installed at Windscale. Is it intended to make special arrangements for the supply of this advanced reactor from Calder Hall?

It is stated in Section 6 that, because of the size of the battery floating on the d.c. busbars, no end-cell switching has been provided, so that the voltage for all the circuits connected to the battery must vary between 210 and 330 volts. About 50 years ago several large batteries—some of them larger than those used in the present case—were used with automatically-controlled regulating switches. In particular, I recollect some large batteries used by the Birmingham Corporation electricity undertaking, which had very large automatically controlled end-cell regulating switches at their Dale End and Summer Lane stations. Alternatively, a number of large batteries with fixed numbers of cells were used with voltage controlled by automatic reversible boosters.

The large variation of voltage in the battery circuits at Calder Hall (between 210 and 330 volts) must evidently involve complications in the emergency lighting system and with the motors connected to the d.c. circuits, and it would surely be advisable to avoid these complications if possible.

Mr. D. A. Dewison: In 1952 the C.E.G.B. (then the British Electricity Authority) were asked to co-operate in the initial design studies for a nuclear power station, and the following information was provided to enable an electrical system to be designed. The station was to be sited adjacent to Harwell, which had an 11 kV board supplied from the Grid, and it was suggested that this could be used to provide electrical power for the new station. There was to be one reactor supplying heat to four heat exchangers, and these were to supply steam for a 44 MW turbo-generator. An auxiliary cooling circuit was proposed, one of the objects of which was to cool the reactor in the event of failure of the a.c. supplies, the motors on this circuit

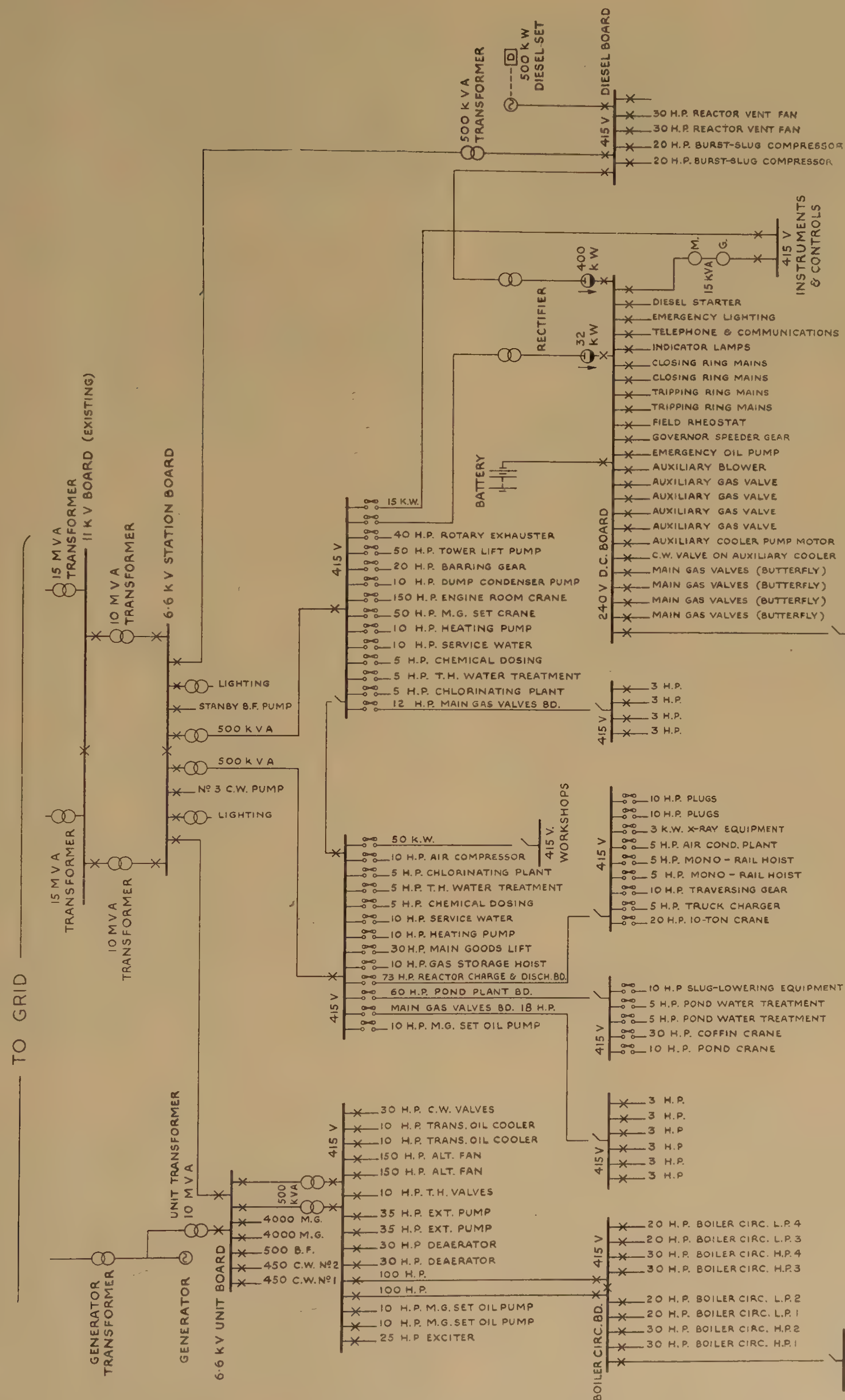


Fig. B.—Electrical system for proposed nuclear power station.

being d.c. ones. A detailed analysis of the power needed for the various auxiliaries had been made.

From this information the electrical system shown diagrammatically in Fig. B was produced. This gave the type of reliability to the generating plant which is generally accepted practice for modern power stations. The vital auxiliaries for protecting the reactor in the event of a failure of the normal a.c. supply were supplied from a special system consisting of a battery and Diesel plant, similar to that shown by the authors. Since that time the plant design has undergone change; there are now two 23 MW generators per reactor instead of one 44 MW unit. The auxiliary cooling circuit appears to have been discarded, the duty of protecting the reactor apparently being taken over by the pony motors on the gas circulators. The station has been resited beside the Windscale factory, and it is evident that the desire to provide maximum reliability of supplies to this factory has been a significant factor in the design of the system for Calder Hall, and is apparently one of the reasons for the adoption of 11 kV as the main voltage.

Mr. T. E. Houghton: A good deal has been heard about brush lives of so many hours, but this is a very loose term unless it is related to the wearing length of the brush. Brush lives should always be given in hours per inch, for this is the only basis which can give a correct appraisal. From my experience with d.c. machines, I would consider 4 000 h/in as poor, 6 000 h/in as fair, 8 000 h/in as good, and 10 000 h/in as first class: I have known instances of Continental machines giving up to 14 000 h/in. This does not mean that machines can be run for 8 000–10 000 hours without attention; to achieve such long lives as these it is necessary to shut down the machine periodically, say once every 2–3 months, to check the brush gear, to adjust the brush tensions to the correct figure (which should be done very meticulously) and to see that the commutator surface is in good condition. Unless this is done, brush lives of 4 000, 3 000 or even 2 000 h/in will be the result.

Mr. J. C. Williams: For the guaranteed electrical supply there are alternative a.c. systems, but in my opinion if the highest degree of safety is required, there really is no choice except a d.c. system, with a battery as the ultimate source of power. The degree of safety may be related to cost, and the plant operator may be given comparative data and asked to choose one of a number of alternatives. A.C. systems must be synchronized at some stage and consequently may suffer instability, but d.c. systems are not subject to these difficulties.

The d.c. system shown in Fig. 5 has the emergency lighting and the switchgear-tripping circuit from only one section of the d.c. busbars. Would it not have been wiser to put these two services on the central section of the busbars, fed directly from the battery?

How much of the 17% station load and the station capital cost arise because the station is optimized for plutonium production rather than for generation? The total of the auxiliary loads given in Table 1 is 13·5 MW. Is the difference between this value and 17% of 92 MW (i.e. 15·7 MW) due to some load not mentioned in the paper?

With the strengthening of safety considerations in the U.K.A.E.A., are arrangements envisaged for an emergency control centre in the event of a nuclear hazard?

Have there been tests of the effect on system voltage when starting the motor-generator set of the Ward Leonard system?

Details of the pressure-type cable boxes mentioned in Section 5.6, would be most welcome.

The voltage variation of the battery seems large; is it a lead-acid or a nickel-alkali type?

Mr. R. D. Trotter: The point has been made several times that at Calder Hall there are separate control rooms for the reactors and the electrical plant, while centralized control is being considered for the civil stations. To mention only one aspect of this question, the Calder Hall turbines are pressure-governed, so that system makes no contribution to the frequency stability of the Grid. This could not be tolerated at the civil stations. In view of this, there are perhaps two alternatives: either automatic control systems must be introduced on the reactors (with some trepidation, perhaps), or connected operation between isolated control rooms will have to be faced. There are other aspects, such as the cost of manning the control rooms, which affect this issue. I believe that the principle of centralized control cannot be abandoned. Perhaps the development of this art will be, when more is known about control systems, to reduce the number of indications required in the control rooms, thereby reducing their size; but hand in hand with this will have to go the use of smaller instruments and miniature control systems.

With an a.c. essential-supply system it is possible to synchronize the Diesel engines during normal operation of the station, and to load them fully by exporting a.c. power to the station auxiliary system. With a d.c. scheme this cannot be done, and unless the station is taken off load at frequent intervals, it is impossible to load the Diesel sets and to know whether they are contributing their full standby reliability.

On control-rod supplies the remark is made that movements are now taking place towards the use of static apparatus. This must be encouraged, since the civil reactor stations will have control-rod systems with many independent groups of rods and the amount of supply apparatus concerned is increasing.

Mr. H. E. Clapham (*at Edinburgh*): All motor starters and circuit-breakers used for motor starting are fitted with a delayed under-voltage release feature. What under-voltage, time and overload trip settings are used; e.g. what current overload causes tripping in 10 min? Are the motors designed to carry sustained overloads or are they m.c.r. machines?

In power-station practice it is usual to specify that auxiliary motors shall remain in service for up to 10 min if the voltage falls to about 70% of normal, the frequency remaining constant at 50 c/s. Is there a similar requirement regarding many of the auxiliary motors at Calder Hall? It is noticed that the short-circuit current of the 2 500 h.p. 740 r.p.m. squirrel-cage motors is $3\frac{1}{2}$ times full load, which would indicate that it is unlikely that such a requirement can apply to these particular motors; moreover, the control-rod frequency-changers will operate on 50% normal voltage, but we are not told for how long.

In general, when an induction motor is running on full load and its voltage is reduced to 70% of normal, the current drawn from the line rises to about 170% of normal full-load value. Thus the stator copper loss becomes $1\cdot7^2$ or about three times the normal full-load value; if this persists for as long as 10 min, it constitutes a very severe overload.

In British power-station practice to-day, motors are almost invariably specified to be maximum continuous rated to B.S. 2613, and also to be capable of remaining in service for up to 10 min if the voltage falls to 70% of normal. These two requirements are contradictory, since B.S. 2613 expressly excludes sustained overloads, and any machine built strictly to it will not carry overloads of this nature without risk of severe damage. If the overload relays are set to permit of these long-duration overloads, they afford only very poor protection against continuous overloading. In practice, it is suspected that overload relays are set without reference to these 10 min overloads, thus making the expensive overload capacity built into the motor unusable. This unsatisfactory state of affairs could be rectified if the 10 min duration were reduced to, say, 1 min or less. The overload occasioned by reduced-voltage running might than be considered as a momentary overload within the terms of B.S. 2613.

Mr. W. D. Garbutt (*at Leeds*): During the last 25 years or so it has been general practice to use rectifiers instead of rotating equipment wherever possible, with the result that they (particularly the multi-anode type) are used almost exclusively to-day. Rectifiers are used satisfactorily with many types of variable-speed drive, and speed ranges of 10 : 1 are quite common and present no problem. Transductors are used extensively for automatic control for starting and the speed control of motors. Many variable-speed drives are arranged so that the adjustable direct voltage from a rectifier is fed to the armature of a motor to give a wide speed range and any further speed range is obtained by field control. Although such schemes are very successful, there are some applications where the Krämer drive in one form or another will be preferred.

Multi-bulb rectifiers are in use and others are now being built for use in Krämer schemes, one very interesting example being the ventilation of mines requiring motors of similar size and speed control to those required for the gas circulators in atomic-energy plant. In these schemes the main driving motor is a standard wound-rotor induction type and the slip energy is taken from the slip-rings through a simple rectifier then fed into the armature of a smaller motor mounted on the shaft of the main motor. Speed control is obtained by varying the field of this smaller d.c. motor.

I should therefore like to know why a Ward Leonard system has been selected for this apparently relatively simple application of running a motor over a speed range of 10 : 1 in one direction only.

Mr. N. Sellers: (*at Leeds*) The authors mention that the mezzanine floor, below the reactor control room, was provided for the marshalling of cables and junction boxes, and it would be interesting to hear to what extent this cable marshalling was carried out. Safety considerations require segregation of the various supply and instrument cables, and although several circuits concerned with one function, e.g. rod control, could be conveniently contained within a single cable, these circuits would arise from adjacent panels in the control room, and bus wiring would be preferable to a marshalling point below the panels. In some instances m.i.c.c. cables have been taken into marshalling kiosks which are virtually straight-through junctions giving greater possibility of faults without apparent advantages.

The paper states there is flexibility in the choice of stand-pipes to be used for control purposes, but what flexibility is available in the control-rod system itself? One of the lantern slides showed the convertor sets and sine potentiometers which provide low-frequency supplies, but are facilities available to permit change-over selection to the various supplies without de-energizing the control-rod mechanism? Can the rods be adjusted relative to each other to assist in flux levelling, or in the case of a control rod being used for fine control developing a fault, can another be selected to replace it without shut-down?

The paper states that the control system must be designed to prevent spurious tripping. What types of spurious and fault trips have occurred at Calder Hall since commissioning, can any conclusions be drawn from these and have changes in the philosophy concerning control reliability or flexibility resulted?

It would be interesting to hear details of the operating experience with the instrument supply. Since the more important instrumentation and protection operates on a two-out-of-three basis, is it not preferable to carry this philosophy further and provide three separate instrument supplies, thus eliminating the transformer change-over system?

It is now $2\frac{1}{2}$ years since the first reactor at Calder Hall was commissioned, and it would be most instructive if the authors could add to their conclusions and give some idea of future trends in electrical installation of nuclear reactors as, for example, at the advanced gas-cooled reactor now being built at Windscale.

Mr. F. Clarke (*at Leeds*): Calder Hall comes within the scope of the Factories Acts as a factory producing plutonium and as a generating station supplying both the national Grid and an industrial establishment.

The description of the station should be completed by including a reference to the 50- and 110-volt circuits adopted by the U.K.A.E.A. as standard for portable equipment.

The fault duties on the 11 kV system and the necessity to use switchgear with breaking capacities of 500 and 750 MVA appear unnecessarily severe. System limitation and switchgear rating might perhaps best be governed by current rating and not by apparent power alone. The proposal has been made that 13·1 kA should be the limiting current on all systems, and this would raise the system voltage to 33 kV for a duty of 750 MVA.

The rocky substratum at Calder Hall presents a difficult problem when considering the earthing system, but putting earth electrodes in the backfill appears to be unsatisfactory and I should welcome more details.

It does not appear from the few facts given that the U.K.A.E.A. has really achieved complete failure to safety, as stated in the paper. It is, of course, almost impossible to ensure 100% failure to safety, but a great deal can now be done in this sphere and further information on this point would be welcome.

The temporary heating arrangements provided for stress relief of the pressure vessel appear excellent when considering the mains voltage supplies and the internal stainless-steel tubular heaters which were used for that particular application. The h.f. induction heaters do not appear to be so satisfactory: the frequency of 2·5 kc/s gives no greater degree of safety from electric shock than 50 c/s.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. N. J. Mackay and E. Hardwick (*in reply*): Before dealing with the detailed questions we will answer broadly those affecting the principle on which we have worked.

Combined Control Rooms.—The questions raised concerning the combination of the electrical and reactor control rooms rightly pointed out there are a number of factors involved in the solution to this problem. Not the least of these is the provision for future reactors at a given site, which might well tend to overburden an already completed control room, particularly when additional test facilities might be required. Also there is the distraction of adding plant in rooms which are continuously operational. Other points to be considered are the physical positions of the reactors and turbine houses relative to each other, the possible risk to extending the control lines, the bringing together of all controls at one point, and whether this indicates a need for local emergency-control positions. These needs must obviously be balanced against the operational staff requirements, but our experience with Calder Hall to date has not indicated difficulties sufficient to change our intentions to provide separate control rooms for our next reactor project.

Alternative Types of Circulator Drive.—The question of alternative drives for main circulators has been much discussed, and here our difficulty has been to obtain data on truly continuously running drives of comparable horse-power to our requirements. Our investigations have generally revealed the fact that the term 'continuously running' has been applied to machines which have, in fact, been shut down for part of the week-end for maintenance. Power-station a.c. variable-speed motors, although running

reliably, have not yet proved to be of such size and speed as to be comparable with our requirements.

Our present investigations for a new project, in which we have considered both steam turbines (normally condensing but capable of running as back-pressure sets) and electrical machines, have resulted in the adoption of squirrel-cage induction motors supplied from mains guaranteed in the same way as at Calder Hall. The condition has been eased here in that control of gas flow is arranged mechanically by throttling, which has enabled us to adopt a constant-speed circulator.

Operation of System.—There appears to be need for clarification of the operating conditions of the electrical network at Calder Hall, and we would confirm that the interconnector between each pair of nuclear reactors is normally closed, thereby providing a duplicate supply to each reactor. The interconnector is sufficiently large to cater for export of power around this system should either of the 30 MVA transformers trip out. Generator earthing is provided for each pair of generators associated with a house load, so that if the Grid supply were lost the reactors might still continue to operate. The double-busbar feature of the 350 MVA switchgear has proved useful in that since completing the original installation we have had to extend these boards, and this has been carried out without affecting the operation of the reactors. Although operation of the original two Windscale nuclear reactors has been discontinued, the continued development of the factory is providing new loads for the system.

Emergency Supplies.—While the discussion has accentuated the diversity of opinion on the question of a guaranteed source of supply, we have had no cause to alter our view that the requirement at Calder Hall was best met by the d.c. system. The d.c. motors have proved reliable, and the fact that they are larger than normal in having to cater for the voltage range 210–330 volts has no doubt contributed to this reliability.

Being rectifier-fed from the a.c. mains the emergency system does not require automatic disconnection to ensure that it will not take on a condition of overload. A nominal 30 min capacity for the battery was arrived at bearing in mind that mains failure might well occur at the most unfavourable time of night and weather conditions, thus retarding remedial action. The question of battery voltage has been raised, but this produced surprisingly little difficulty, stabilizers being required only for the emergency lighting and some of the switchgear closing supplies; these have caused no trouble, whereas end-cell switching could affect the whole battery and switchboard.

With regard to the individual questions not answered collectively above we would comment as follows.

Mr. Crawford.—We attempted to retain the old title of 'pile' for nuclear reactors, but for conformity we must now refer to either nuclear reactors or electrical reactors.

Mr. Makin.—With regard to a.c. and hybrid emergency supply schemes, we have had to face this problem on other reactors where temperature conditions have made d.c. motors difficult. In such cases we have always arranged that the motor-alternator sets carry load continuously, and there is no reversal of flow under emergency conditions on change from normal operation. The special problem of recovery and discriminating protection of the small motor-generator sets, and their relatively large loads, has needed careful investigation.

Mr. Ball.—We took particular care to separate instrument cables, in the reactor cable mezzanine, and are not aware of any serious trouble. The edict on two unrelated faults was not propounded as such at the time, but since Calder Hall requires to be shut down for refuelling, maintenance can be phased more easily than with a C.E.G.B. station, and at low power the battery time could be extended. At the worst, a temporary connection could be arranged to one of the other reactors. Failures so far have been on the starting equipment, not the engines.

Mr. Connon.—The intertrip between the reactor and the turbine tripping circuits was included because it was thought that steam pressure would drop extremely rapidly in the event of a reactor shut-down. It has been established that the reserve of steam is, in fact, sufficient to prevent immediate motoring conditions, so that the sets are now being shut down by hand, the intertrip having been disconnected.

Mr. Tozer.—Marshalling kiosks were required because of space limitation in the instrument panels, but they did provide the facility of terminating the cable runs irrespective of instrument-panel delivery. A separate 50-volt telecommunication battery is provided for the principal telephone-type alarm and miniature control equipment. It was considered that on-load brush changing on the circulator machines was precluded by the high voltage and lack of accessability.

Mr. Evans.—Works tests included brush-life investigation, but the time available was limited. Brush life would permit approximately 5 months continuous working of the control-rod convertor sets, but the sets are changed over at intervals of 500 hours for maintenance.

Mr. Dewison.—The scheme shown in Fig. B indicates a unit scheme for the generator and circulator, unless it was intended to run the unit transformer in parallel with the station transformer, which might prove difficult. With a 100% steam-dumping facility, duplicate feeds to the circulators would be required.

Mr. Williams.—Discrepancies in the tabled figure and the 17% house-load figure arose from the fact that the circulator load increased considerably between the two readings, owing to modified reactor parameters. The 11 kV system was subject to an analyser study including recovery of the circulator drives. The batteries are all of the lead-acid type. So far as we are aware, the provision of full steam dumping facilities is the only item specific to the need to produce plutonium. No emergency control centre is envisaged for the Calder Hall station.

Mr. Clapham.—Essential drives are all direct-current, owing to the no-break feature, but other important auxiliaries were specified for 70% voltage operation for 10 min. The main circulators have, in fact, a limited ability to recover from system transients, although on power requirements it was thought at the time that there was a substantial margin. The control-rod convertor sets, however, looked as if they would be fully loaded, and hence these were 'weighted' with the requirement to operate at 50% voltage.

Mr. Garbutt.—Our remarks under the general heading of circulator drives apply here. We considered the rectifier-fed d.c.-motor arrangement, but were somewhat concerned at the time with the possibility of current surges in the motors, caused by supply-voltage variations. Additionally, the rectifier merely replaces certain of the rotating machines but still leaves the very large d.c. variable-speed motor, with its brush-maintenance problems. The Krämer drives examined so far have been very much smaller than our requirement and have not provided the assurances we required.

Mr. Sellers.—The questions raised accent the most important point in that the electrical design engineer, in providing individual supplies and control for the many types of main and auxiliary drives required in reactor engineering, must maintain their integrity to the maximum, and at the same time must provide for the necessary flexibility for operation and maintenance of the plant. This obviously limits the amount of marshalling of cables which can be carried out, and as an instance, no pony-motor supplies or controls were allowed to come together except for their feed from the main d.c. switchgear. Spurious tripping due to electrical faults has been very moderate indeed, and no

design action other than that outlined in the paper is at present envisaged. Control-rod drives are quite flexible, so that it is possible to effect on-load change-over of any rod from the convertor sets to the sine potentiometer and from one set to the other.

Instrument supplies are now being supplied on new reactors from three separate motor-generator sets. With regard to future trends, the new advanced gas-cooled reactor is being provided with single-speed squirrel-cage induction-motor drives for the circulators; but since these are within the pressure system and required to work in carbon dioxide at $300 lb/in^2$, this, together with $3 \cdot 3$ kV cable seals, has given rise to attendant difficulties.

Mr. Clarke.—Portable tools and transportable equipment, such as the main cooling fans provided on the reactor cap, are supplied at 50 volts and portable lights at 25 volts. The problem of having 500 and 750 MVA switchgear at 11 kV was complicated by the requirement of the relatively large house load of the main circulators, having duplicate connections to the Grid system, and the station generation at this voltage.

Earth electrodes in backfill were not relied upon, and additional earth pits were established at each end of the turbine house, all being bonded together.

While most of the reactor equipment fails to safety in that de-energizing provides automatic operation, standard circuit-breakers requiring trip coils to be operated have their coils and supply monitored and alarmed at all times. Stress relief using a $2 \cdot 5$ kc/s supply was used for induction heating the welded joints of the heat exchangers and provided a rapid method of carrying this out. Distribution busbars were run in trenches with interlocked covers and connecting points to minimize risk from this source.

621.311.25 : 621–5

The Institution of Electrical Engineers
Paper No. 2812 S
Dec. 1958
©

THE DESIGN OF ELECTRO-MECHANICAL AUXILIARIES DIRECTLY ASSOCIATED WITH POWER-PRODUCING REACTORS

By A. E. HARWOOD, P. SCOTT, M.A., Graduate, and B. H. STONEHOUSE, B.Sc.(Eng.), Associate Member.

(*The paper was first received* 16*th October*, 1957, *and in revised form* 3*rd November*, 1958. *It was published in December*, 1958, *and was read before the* North-Western Centre 6*th January*, *and at a meeting of the* Supply Section *held in conjunction with the* British Nuclear Energy Conference 28*th January*, 1959.)

SUMMARY

The paper deals with the novel problems encountered in the design and construction of the electro-mechanical plant directly associated with the reactor in a base-load nuclear power station of the gas-cooled graphite-moderated natural-uranium type. The problems arise from the fact that the plant must operate in radioactive areas and certain parts of it are immersed in the reactor coolant.

Two distinct features are considered, namely the materials of construction and the control of the plant. The materials are required to resist the effects of radiation and temperature and must be compatible with the coolant.

The features required by the operator for controlling the plant from a remote point and the need for the highest possible reliability are considered.

(1) INTRODUCTION

For some years it has been necessary to design equipment to work under the radioactive conditions which exist in research reactors and their associated experiments. More recently, with the advent of base-load nuclear power stations of the pressurized-gas-cooled graphite-moderated natural-uranium type, it has become necessary to design plant of greater complexity which also has to work under more arduous conditions. This plant is associated with the charge and discharge of fuel from the reactor, the servicing of the reactor while it is on load and the reactor control-rod mechanisms. The paper outlines the conditions under which the plant is required to work and describes some of the novel design problems encountered, together with typical solutions.

The plant is required to work continuously or intermittently in reactor coolant gas and may be subject to radiation damage. The principal sources of radiation are the reactor, the irradiated fuel elements and components, such as control rods, which become active by virtue of being in the neutron flux for appreciable periods. The novel problems which arise in the design of plant working under these conditions fall into three main groups, namely the materials of construction, the method of motivation and the method of control. For plant immersed in the reactor coolant one must consider, not only the possible effects of radiation, but also its compatibility with the coolant and other materials in the reactor core. Problems arise in the second and third groups because the plant must have the highest possible reliability and must be entirely remotely controlled.

Items of plant working under these various conditions are seen in Fig. 1, which shows a cross-section of the structure of a gas-cooled graphite-moderated natural-uranium-fuelled 550 MW thermal power reactor. Mounted above the biological shield is the reactor servicing machine which is used for

(*a*) Withdrawing and replacing the control rods and their mechanisms for maintenance and repair.
(*b*) Insertion of fuel elements with thermocouples attached.
(*c*) Emergency extraction of fuel elements from the core.
(*d*) Lowering a television camera into the reactor vessel.

The authors are with the General Electric Co., Ltd.

The first three types of operation can be carried out with the reactor on load, so that the materials of construction inside the machine must be compatible with carbon dioxide at temperatures ranging up to 400° C and must withstand small amounts of neutron and γ-radiation. Since radiation shielding is necessary, the machine is remotely controlled.

Enclosed in the standpipes projecting through the top biological shield are the control-rod mechanisms. These are adequately shielded and operate in carbon dioxide at a normal temperature of 40° C: it is vital that the utmost reliability is achieved in their operation.

The charge-discharge machine beneath the reactor, as its name suggests, is used for handling the uranium fuel in and out of the reactor while it is on load. The majority of the machine's mechanisms operate in carbon dioxide at 100° C, but for those parts which are raised through the biological shield the temperature approaches 200° C. These parts are also subject to high neutron and γ-radiation fluxes. The inside of the machine is subject to damage by a beam of neutrons which streams down the standpipe and to γ-radiation from the discharged fuel elements. Adequate local shielding and remote control of the machine are again required.

Further machines and manipulators are required for handling the irradiated fuel elements when they are removed from the charge-discharge machine. The manipulators work in air or water and are subject only to γ-radiation.

(2) RADIATION DAMAGE

Apparatus working inside the reactor pressure vessel while the reactor is on load is subject to an intense flux of 10^{10} neutrons/cm^2/sec. The holding magnets for reactor shut-down devices working in the flux and at 350° C have been designed using ceramic insulated coils, but the authors have had no operational experience with them.

The irradiated fuel elements from a single channel in the reactor have a source strength of approximately 80 000 curies a quarter of an hour after discharge. The γ-radiation emitted would seriously reduce the insulation strength of a normal class-A-insulated electric motor if it stood for more than 500 hours at a distance of 2 ft from a stack of the elements.

For the type of plant which is operative in a neutron flux only for short periods the irradiation of metal and inorganic parts need be considered from but a single aspect. The absorption of neutrons may render the parts radioactive, making handling and maintenance a problem. For instance, the manganese and cobalt in the steel used for making the reactor service-machine grabs, which are lowered into the core, become active, and the precaution is taken of using steels with a low percentage of these materials.

Significant radiation damage is sustained by the organic materials used for insulating electrical devices, e.g. cabling, sealing gaskets, paints and greases. Studies of the effects of radiation on a range of these materials have been carried out and the nature of the damage is understood. Difficulties arise

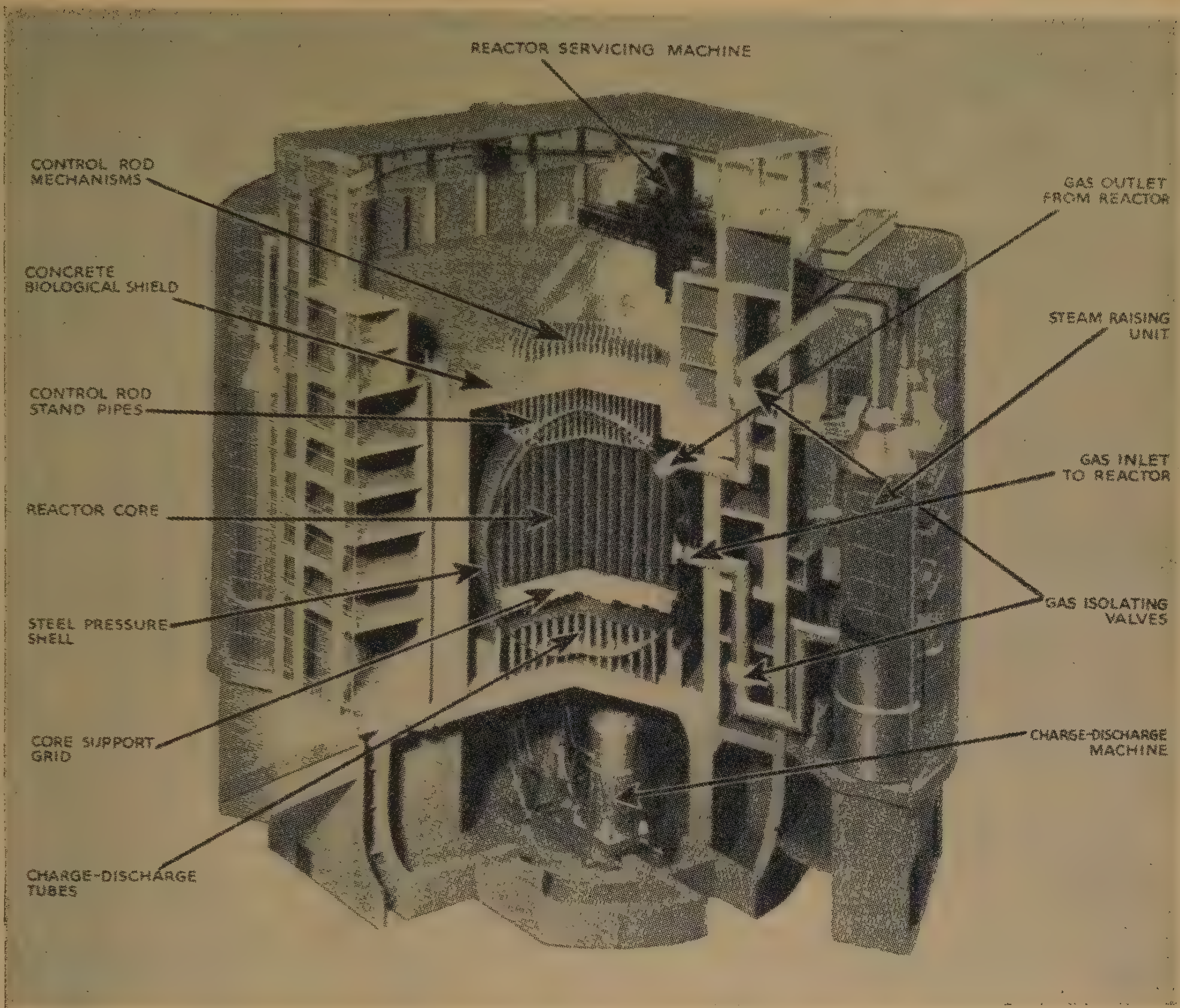


Fig. 1.—Cross-section of power reactor.

in applying the data at present available to a given problem, because they often refer to a different radiation-flux spectrum and to different ambient conditions—both of which can significantly affect the damage. The assessment of the resistance to radiation damage of any device can be based only on a study of the individual materials of construction, since there are little published data indicating operating experience of complete assemblies such as electric motors. The changes in the mechanical properties of the material normally become significant before any appreciable change takes place in the electrical properties. Final selection of a material must be based on a study of its properties over a given life.

The electrical insulating materials for working under radiation conditions may be roughly classified as follows:

Good	*Fair*	*Poor*
All ceramics.	Silicone-bonded glass.	All cellulose compounds.
Mineral-filled phenolics.	Nylon.	P.T.F.E.
Polystrene.	Polyesters.	
Polythene.	Cellulose-filled phenolics.	
	P.V.C.	
	Melamine.	

An example of the type of construction used is the slip-ring column shown in Fig. 2. This is required to work in a high γ-flux, and all the insulation has been made in glass-bonded mica. All induction motors for the same machine are constructed with silicone-impregnated glass-insulated coils in mica-lined slots. The terminal voltage of the machine is restricted to 110 volts so as to decrease the changes of insulation breakdown. Phenolic-bonded asbestos is used for the motor brake-lining.

Inside the charge and service machines the flexible cables required to work at temperatures up to 400° C are constructed of nickel conductors covered with four layers of glass braid and asbestos alternated and sheathed in a stainless-steel braid. The wear which occurs during flexing of the cable results in the formation of small amounts of glass dust which may not be fully contained by the braid. A glass fibre of very low boron content has been specially selected for the cable, to ensure that any such dust does not have a high neutron-capture cross-section.

For flexible cables used in normal air, for instance on a power manipulator, p.v.c. insulation with an inorganic pigment is used in preference to polythene, owing to its greater flexibility,

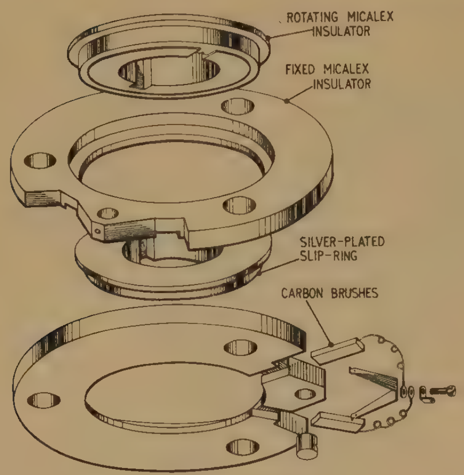


Fig. 2.—Slip-ring column.

although the physical properties of the latter are less affected by radiation. The flexibility of polythene is also adversely affected by radiation damage.

(3) PLANT IMMERSED IN REACTOR COOLANT

Where the equipment is required to work in the carbon-dioxide coolant of the reactor, special attention must be paid to all the materials of construction. As well as the normal design requirements, the material must not react with carbon dioxide, must be suitable for the temperature, be compatible with fuel-element canning material, and have a low neutron-capture cross-section. The first two requirements do not present many serious problems which cannot be solved with well-known materials.

If non-compatible materials or those with high neutron-capture cross-sections are carried over in the coolant to the core, the performance of the reactor is adversely affected. Materials such as cadmium, boron and the rare earths have high neutron-capture cross-sections, and their presence in the reactor core would result in a decrease in the net reactivity and hence either a lower fuel burn-up or a lower operating temperature. The non-ferrous metals such as copper, aluminium, lead and zinc react with the magnesium alloy used for canning the fuel elements to form low-melting-point eutectics; thus, even small particles of the material settling on the outside of the fuel element could weaken the can and cause a leak of fission products.

The result of these limitations is that the greater part of the plant is made in ferrous material. Electric motors and solenoids are wound with copper, but are totally enclosed. Rubbing surfaces are avoided as far as possible, and, where necessary, slip-rings are made in either steel or nickel.

Since the mechanisms of the service and charge machine are in the carbon dioxide for only part of their life, the remainder of which is spent in the normal slightly damp atmosphere of a power station, attention must be paid to their surface finish. Nickel and chromium plating may be used, but are expensive. Epikote-resin-based paints with organic pigments are used for finishing the insides of the machines. The number of colours available is small, but the major components are finished in pastel shades of differing colours. The different colours are used to improve the contrast between the components when viewed by a television camera.

(4) REMOTE CONTROL OF PLANT

In order that some of the problems which arise in the design of the plant handling active material may be more fully appreciated, the operations of one of the six main mechanisms in the reactor servicing machine will be described in detail. The mechanism is used for the withdrawal or insertion of a control rod and its driving mechanism while the reactor is on load.

One complete reactor service machine, as shown in Fig. 3, consists of a pressure vessel approximately 9 ft in diameter and 40 ft long. This is mounted on a crab with a cross travel of 45 ft and a long travel of 120 ft. The machine operator is accommodated in a suitably shielded control room at one end of the run, from which it is possible to view the whole of the reactor cap through a shielded window.

The sequence of operations involved in changing a control-rod mechanism for maintenance is outlined below, and the position of the machine mechanisms during this sequence is shown in Fig. 3.

(*a*) Prepare appropriate control-rod standpipe by lowering over it a distance piece, lowering the control rod requiring maintenance fully into the reactor and adjusting the position of the other control rods as necessary. Time: 11 min.

(*b*) Position service machine over dummy standpipe and pick up new control rod and mechanism. Time: 13 min.

(*c*) Centre machine over appropriate standpipe to accuracy of 0·1 in and seal on to distance piece. Time: 8 min.

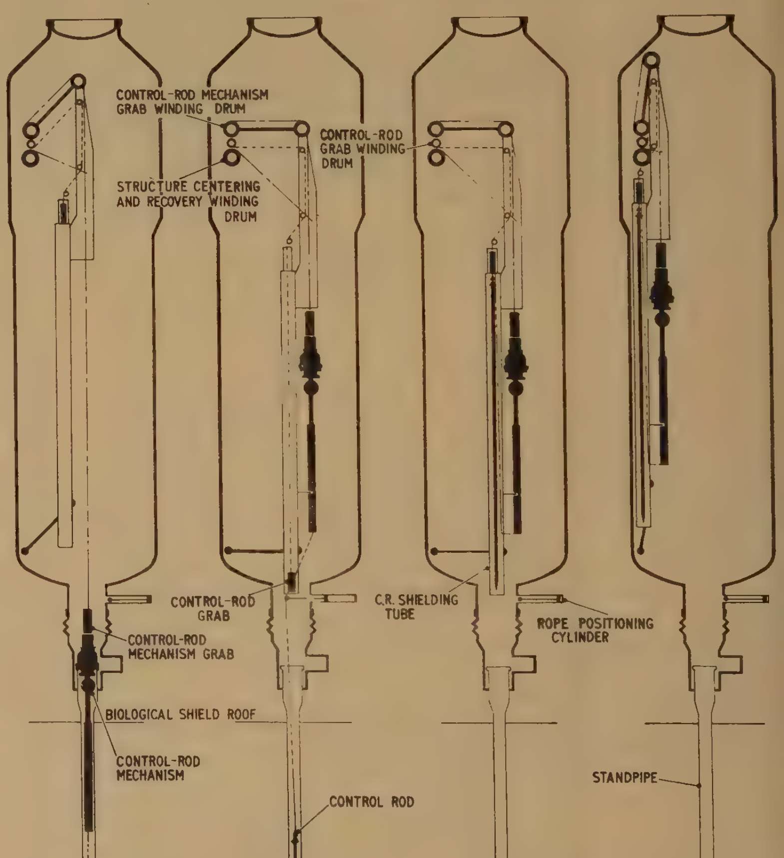


Fig. 3.—Cross-sections of reactor servicing machine.

Position 1. Control-rod-mechanism grab lowered.
Position 2. Mechanism raised, control-rod grab centred.
Position 3. Control-rod raised into shielding tube.
Position 4. Control-rod mechanism stowed.

(*d*) Purge the air from machine and fill with carbon dioxide to reactor pressure. Time: 15 min.
(*e*) Unseal standpipe, lower grab, pick up mechanism, simultaneously withdrawing control rod from reactor core. Time: 3 min.
(*f*) Raise control rod fully into shielding tube inside machine. Time: 17 min.
(*g*) Repeat operations (*c*)–(*f*) in reverse order, with the new control rod being lowered into the core. Time: 45 min.
(*h*) Position the machine over a hole in the mortuary on the reactor cap and discharge the old mechanism. Return machine to parking position. Time: 20 min.

Analysis of the sequence shows that a total of 57 mechanism operations taking 121 min is involved, and of these, 23 are carried out during the hour the machine is sealed to the standpipe. The active control rod is in the machine for 55 min, during which 26 mechanical operations take place.

(4.1) Types of Drives

It is necessary that the mechanisms should have the highest possible reliability. If the machine failed in any way while it contained the active control rod, the repair staff would be subject to a dose of radiation. Further failure to reseal the standpipe with either the old or new control rod mechanism would make it necessary to depressurize the reactor, with the consequent loss of over 100 tons of carbon dioxide, and also of the station output.

Shielding is incorporated in the machine, so that, under the worst emergency conditions when the machine contains active material, a repair team could work on it for one hour without receiving a dose exceeding 10 mr. To achieve adequate shielding the control rods are surrounded by 4 in of lead. To facilitate the work of a repair team the drive shafts for all the significant mechanisms are brought out through the pressure-vessel wall by means of Hyseal couplings and the shafts have squared ends to take manual drive handles. For this reason, the carbon-dioxide-operated cylinders which were used in early designs for operating link mechanisms have been superseded by some form of rotary drive.

To improve reliability, the basic design of the mechanisms is simple and high speeds and accelerations are avoided, particularly since the shafts run in dry bearings at 100° C. The majority of mechanisms require drives of only 1–2 h.p., and squirrel-cage induction motors are used largely on account of their reliability and high power/size ratio. For motions where two speeds are required a second motor or a double-wound machine is used in preference to a remotely controlled two-speed gearbox.

Squirrel-cage induction motors were selected for the drives of a power manipulator working in radioactive areas. These drives were required to have an output of 0·1 h.p. at maximum speed, with an 8 : 1 speed range when driving constant-torque loads. The alternative of pneumatic or oil-operated devices was considered, but rejected on account of the difficulties of piping the supplies to the remote parts of the machine, and of ensuring that these did not leak into the operating area. Variable-frequency induction motors were used because of their high reliability, high power/size ratio, the absence of brushes and the fact that it is not necessary to insulate small rotors with materials resistant to γ-radiation damage. The 100–12·5 c/s supply required was obtained from variable-speed inverter sets with saturable-reactor control of the armature voltage.

(4.2) Position of Operator

The operator of a machine could be accommodated in a cab on the machine, surrounded with the necessary shielding. For instance, the operator of the service machine could be positioned on the main crab. This would have the advantage of permitting manual operation of a few of the drives and of simplifying the control gear and viewing arrangements. These advantages are considered to be outweighed by those accruing from remote control, which permits the use of a lighter biological shield on the machine, with the consequent easing of space and structural problems. The control gear can be mounted in an area where it is readily accessible for repair in the event of failure. The operator has a greater freedom, in that he is not restricted to remaining in a limited area behind a biological shield for at least an hour while the machine is active, nor is it vital to provide him with an assistant. The decrease in the cost of the shield compensates for the increased cost of the control gear.

(4.3) Indication Equipment

Since the service-machine mechanisms cannot be seen by the operator, it is necessary to provide sufficient reliable indication equipment to enable him at all times to be able to judge precisely how each mechanism is functioning.

The control desk for the reactor servicing machine is shown in Fig. 4. The desk is mounted in a shielded control room at the end of the machine travel, with a view out over the reactor cap. The sequence control switches are mounted in the front centre section of the desk, with the initiating switches for the individual mechanisms mounted on the left- and right-hand sides. Mounted above the mechanism switches are small mimic diagrams which are illuminated to show the position of the mechanism being controlled. These mimics are augmented by indicating instruments where a high degree of positional indication accuracy is required. Above the centre section of the desk is a mimic plan of the reactor cap showing the plan position of the machine and the standpipe positions.

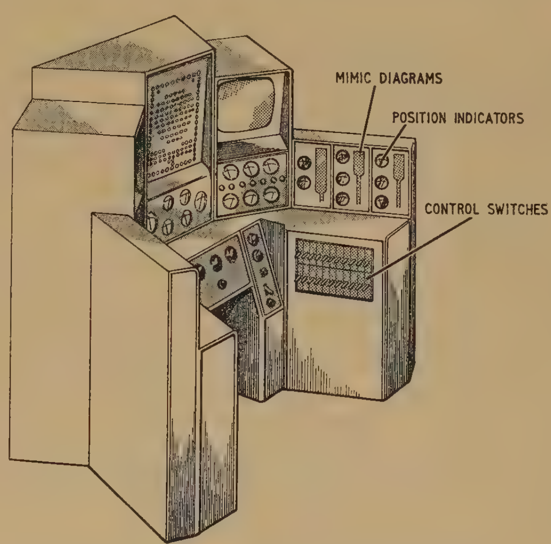


Fig. 4.—Control desk of reactor servicing machine.

(4.4) Television Equipment

The closed-loop television equipment shown on the control desk is incorporated in the machine and indication equipment for three reasons, namely

(*a*) The operator has a better understanding of what is actually taking place inside the machine.
(*b*) The direct vision serves as a check on the normal indication equipment. It is not, however, allowed to supersede this, since it is desirable at all times to have sufficient indications to enable an operation to be completed in the event of a circuit-component failure.
(*c*) In the event of maloperation of the machine it may be possible

for the operator to stop the operation before serious difficulties arise, and the direct vision is invaluable in deciding what course of action is to be taken before any maintenance staff enter the active area.

The reactor service machine is equipped with two cameras. One is in the head of the vessel, and has interchangeable lenses used for viewing either the mechanisms at the head of vessel or the seal face of the standpipe. The other is mounted on the side of the vessel and views objects as they are drawn up through the throat in the base of the vessel.

On the charge machine television cameras are used as final-position detectors; this being possible because, in the event of a camera breakdown before the positioning operation is complete, access for repair is permissible. The machine has to be positioned to an accuracy of 0·1 in under any of 101 standpipes. Tangential and radial datum marks are provided on the sides of the standpipes and on the nozzle of the charge machine, the pairs of lines being viewed with two cameras until both coincide. This scheme is cheaper than using position detectors mating with accurately machined datum faces on the standpipes.

(4.5) Sequence Control

The example of the changing of a control rod and mechanism shows that 57 distinct operations must be initiated over a period of two hours. In some sequences the number of operations rises to 80. The design of control gear for such remotely driven electro-mechanical plant always involves careful consideration of how much of the control should be vested in the human operator and how great a reliance can be placed on automatic control features.

High-grade operators cannot be spared for routine driving of the machine, so the choice lies between using either fully automatic control or a semi-skilled operator, whose interest in the job must be maintained. Experience with this type of plant working in hot carbon dioxide is very limited, and there is a certain reluctance to use fully automatic controls until more operational data are available. However, it is considered that certain sequences should be partly automatic, and wise selection of these controls will result in a better overall operational performance even though the equipment fault rate may be slightly increased.

The control equipment is designed on the basis of indicating both the operations in progress and the completion of each operation. The detection of the finish of one operation sets the control circuits so that the next operation may be initiated. The sequences of operations are grouped so that once the first operation is initiated the machine carries on until the group is complete. The end of a group is arranged to coincide with some operation either where it is vital that the operator should check the satisfactory state of the machine before proceeding further, or where the operator exercises some definite skill and judgment in the control of the subsequent operation. For example, the control-rod-mechanism recovery grab is centred into the middle of the service-machine vessel and lowered until the grab pawls indicate that the grab has correctly located on the head of the standpipe. The initiation of 'grab raise' is the responsibility of the operator after he has satisfied himself that the grab is correctly located.

A switch enables the operations to be stopped immediately and control to be transferred to the individual mechanism control switches, which are used when the normal routine must be departed from because of a machine fault or some unforeseen occurrence.

All the sequencing circuits are designed so that modifications to the sequence are easily accomplished after operational experience has been obtained.

Certain preventative interlocks are also incorporated in the circuits to ensure that the machine cannot be damaged by maloperation. For instance, it is essential to prevent more than one of the six main mechanisms in the service machine being driven to the centre of the vessel at any one time.

(5) CONTROL-ROD DRIVE UNITS

(5.1) Control-Rod Mechanisms

The principles of operation of control rods in a reactor have been previously described in papers before The Institution, and the design of the control-rod mechanisms is influenced by the factors discussed in the present paper. The control-rod mechanisms are housed in standpipes mounted above the biological shield but directly connected to the main pressure vessel. Each control rod, weighing between 90 and 150 lb, is suspended from its mechanism by a stainless-steel rope. A total of at least 100 such units may be required for a 500 MW thermal power reactor.

The performance required of a unit is to hold the rod indefinitely at any set position, to be able to move the rod in and out of the core at a known slow rate, and to insert the rod at a controlled high speed during an emergency reactor shut-down. A typical unit would be required to withdraw the rod a total of 21 ft from the reactor core in 8 hours and to insert the rod in 8 sec during an emergency. The initial mean acceleration under these conditions must be $2{\cdot}5\,\mathrm{ft/sec^2}$ and the final velocity less than 1 ft/sec.

The highest possible reliability is essential, since the units will normally be available for maintenance only once a year, and it is impossible to run the reactor at full power with more than a few units faulty. Failure of the units to insert the rods in an emergency is serious but not catastrophic. The requirements that all units in the standpipes should be as simple as possible for high reliability is also economically sound.

A single set of more-complex externally-mounted control equipment can be used for a large number of rod mechanisms, making the net cost per mechanism quite small.

To ensure the reliability of the emergency insertion of the rods it is essential that this should be independent of the normal power supplies, so the forces due to gravity are used for this purpose.

Pressure-vessel construction problems dictate that the control rods should be mounted in the coolant gas. Consideration of whether the winding-drum driving unit should be mounted inside or outside the pressure vessel showed that this was dependent on designing a shaft seal to withstand 10 atmospheres, to be gastight and of low friction torque. It was therefore decided to mount the driving unit inside and to use an electric machine. The problems of radiation damage to the driving mechanism do not arise because adequate shielding is provided by means of the plug in the biological shield.

The mechanism is in contact with the reactor coolant, although except when it is being withdrawn for maintenance purposes, the only direct path is down the ½ in-diameter hole through which the rope passes. To ensure that the conditions of compatibility are met, the whole of the mechanical parts are made in steel or cast iron and all the electrical equipment is totally enclosed. The main bearings are grease-packed sealed ball-races.

The gas temperature at guide-pan level is 400° C, but the shielding plug acts as a thermal barrier, and under no condition does the temperature of the gas surrounding the mechanism exceed 100° C.

One design of mechanism resulting from these considerations is shown in Fig. 5. The design is based on using a single electric machine for holding, moving and braking-rod travel. This arrangement eliminates the need for employing any

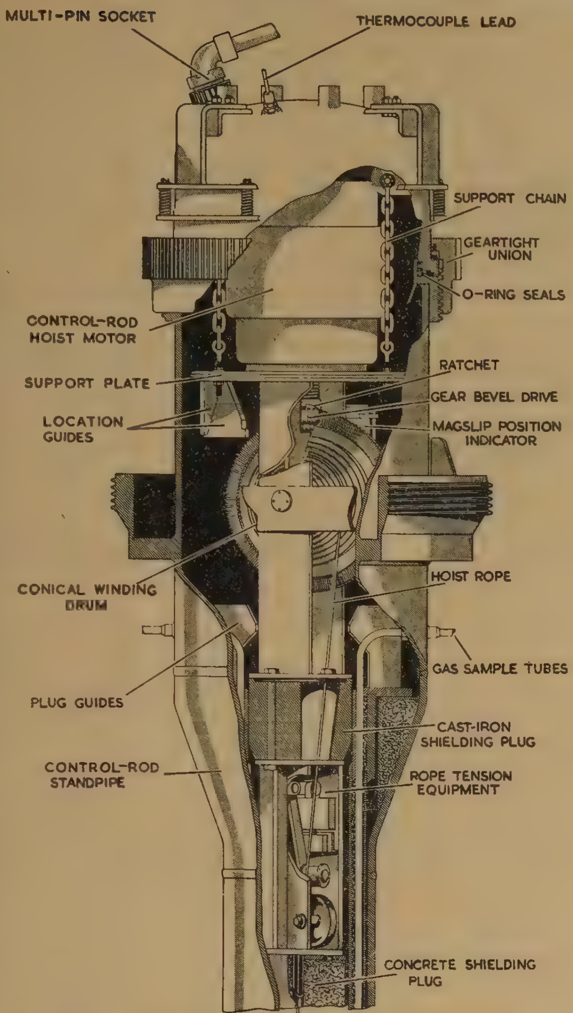


Fig. 5.—Cross-section of control-rod mechanism.

clutches or mechanical brakes inside the standpipe and tends to a simple design of mechanism. The mechanism consists essentially of a vertical-spindle permanent-magnet-rotor electric motor driving through a ratchet and bevel gear a conical winding drum taking up the control-rod suspension rope. The stator has a normal 3-phase winding which is energized with direct current for holding the rod position and with low frequency for moving the rod.

The electromagnetic braking is obtained by means of the permanent-magnet rotor, whose rotation induces losses in a high-resistance cage winding in the stator slots. Ignoring the variations in air-gap flux with machine load, it can be shown that at low speeds the cage losses are proportional to the square of the speed. As the speed rises the index of the speed, N, falls until, at very high speeds, the losses are almost independent of speed. Tests carried out on a machine showed that over the speed range 300–1 000 r.p.m. the total losses including windage and friction varied as $N^{1.8}$.

In order to obtain a high initial rod acceleration of $2 \cdot 5$ ft/sec^2 during an emergency drop, it is necessary to keep the inertia coupled to the winding drum to a minimum, and hence also the gear ratio between the drum and the motor rotor. A conical winding drum is used to obtain the required velocity/time characteristic for the rod.

An emergency drop is initialled by de-energizing the 3-phase holding windings on the motor so that the rod and mechanism are free to start accelerating under the influence of gravity. When the rod is raised the rope is lying in the grooves of maximum diameter, thus ensuring a high initial accelerating torque. As the rod descends, the rope leaves the drum at a decreasing radius, so that the torque on the drum is reduced; however, the speed of the rotor remains high, with the result that the braking torque exceeds the accelerating torque and the rod velocity falls to a final safe low value. The velocity/time characteristic of the rod is shown in Fig. 6 together with the speed of the rotor.

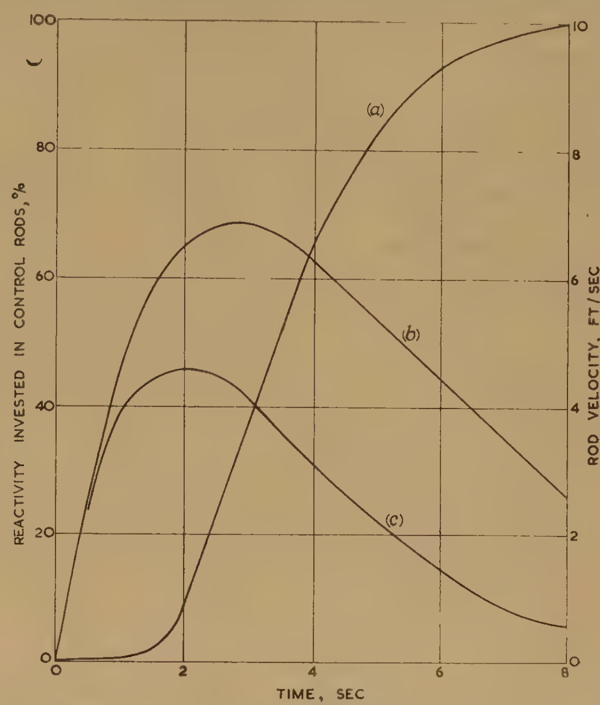


Fig. 6.—Shut-down performance of control rod.

(*a*) Reactivity/time characteristic.
(*b*) Motor speed/time characteristic.
Peak speed = 980 r.p.m.
(*c*) Rod-velocity/time characteristic.

The induced peak voltage across the windings is kept down to 450 volts as a precaution against breakdown of the wiring insulation at some point. Such an accident would greatly increase the time of rod insertion.

The direct current used for energizing the 3-phase holding winding is derived from metal rectifiers. To initiate the emergency drop it is not sufficient to open-circuit the a.c. supply to the rectifiers, for these must be disconnected from the motor terminals lest they act as a low-resistance path across the motor terminals during alternate half-waves of generated voltage. The current flow under these conditions greatly increases the braking on the rotor, so that the time of insertion rises to 6 min. However, all the motors in a group are left with their windings connected to the common supply lines. With this arrangement, synchronizing current flows between motors and ensures that they remain in step until a low speed is reached during the emergency drop.

The effect of bearing friction on the distance/time characteristic is shown in Fig. 7, together with the characteristic curves for the rod travel when starting with the rod partially inserted into the reactor core. The bearing friction has very little influence on the distance the rod is inserted during the first three critical seconds. Thus the mechanism performance will not seriously be affected by an increase in friction between maintenance periods.

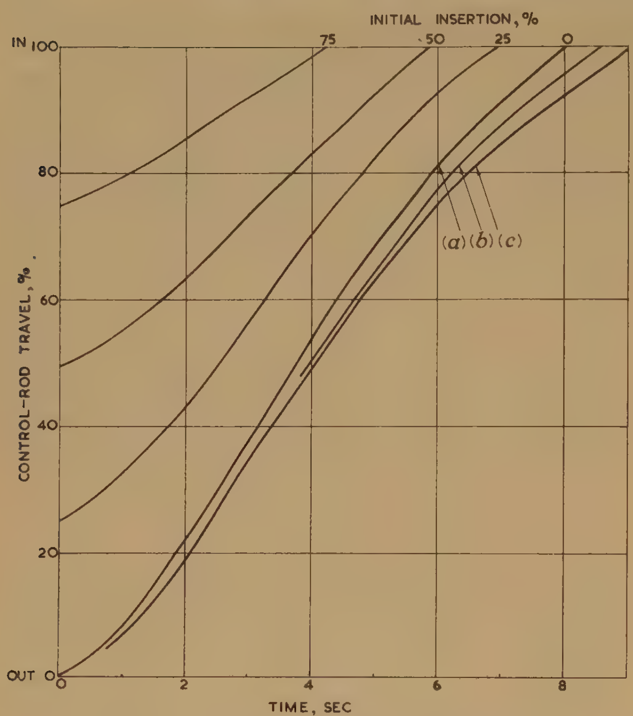


Fig. 7.—Control-rod travel following reactor trip.

Bearing friction torque	lb-ft.
(*a*)	0·5
(*b*)	1·0
(*c*)	2·0

The effects of varying the control-rod weight and the resistance of the cage winding are shown in Fig. 8. With the high-resistance cage the time of fall is not greatly affected by the weight, but the terminal velocity of the rod rises rapidly. However, by matching the cage resistance to the rod weight, approximately constant values for time of fall and terminal velocity may be obtained.

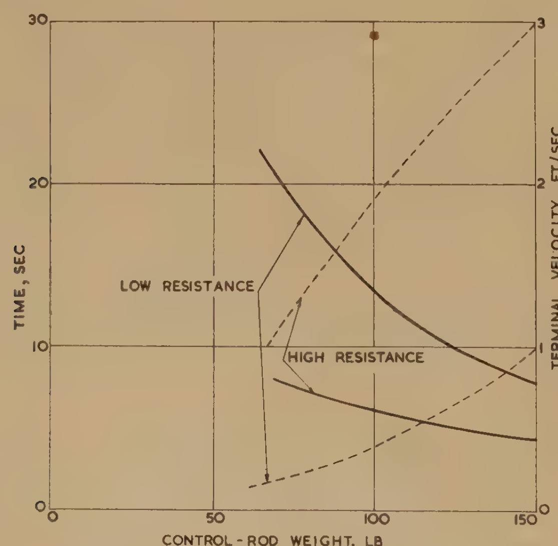


Fig. 8.—Effect of cage resistance on shut-down performance.

——— Time characteristic.
— — — Terminal-velocity characteristic.

(5.2) Motor Supply Equipment

The emergency-drop performance described has a profound effect on the design of the normal 3-phase winding in the stator which is used when the machine is run as a normal synchronous motor. The number of turns per phase are limited by the fact that voltage induced during an emergency shut-down must be kept to a few hundred volts. There is thus a compromise between this condition and having to use heavy-current leads to each machine.

As a result of the low gear-ratio between winding drum and motor rotor, the frequency of the supply required for driving the motor varies between 0·009 and 0·36 c/s. A d.c. supply is also required for holding the rods stationary. One advantage of the low frequency of the supply is that the losses induced in the cage winding by transformer action from the main 3-phase winding are negligible. The transition between the direct holding current and the alternating driving current is required to be carried out without switching if the possibility of leaving the motor de-energized for even an instant is to be avoided. This dictates that the same unit should be used for generating both supplies. The fact that the rod motors are energized continuously while the reactor is in use suggests that, for high reliability, the generating plant should be static rather than rotating.

The schematic of a supply unit is shown in Fig. 9. Connected to the 50 c/s supply are the 3-phase delta-connected primaries of a unity-ratio induction regulator used as a phase-shifter and a 4-winding unity-ratio transformer. The phase-shifter secondary terminals are connected one to each of the star points of the secondary windings of the transformer. The resulting nine output terminals are connected to three step-down transformers in such a manner that the relationship between the voltages connected to each transformer is the same as normally applies in a 3-phase circuit. The step-down-transformer outputs are rectified and applied to the motor windings after passing through switching contacts. The output of the unit when the induction regulator is stationary is equivalent to the instantaneous voltage in a 3-phase system. The negative halves of the sine waves are obtained by means of the cam-operated switching contactors. The low-frequency supply is obtained by rotating the induction regulator at a speed approximately proportional to the frequency required. Cam-operated contactors are used in preference to slip-rings and 2-segment commutators since problems arise in the heating of the contact surfaces whilst the unit is stationary. Furthermore, the width of the brush has the effect of distorting the sine wave of voltage output near the voltage zero, and this results in motor cogging. For instance, if a brush-face width which subtends 5° at the centre of the commutator is used, the motor rotor moves forward 3° at the instant the brush short-circuits the two halves of the commutator, this effect occurring six times per revolution in a 6-pole motor.

Consideration was also given to operating the motor from the positive half-cycles only of the rectifier output. This would have the advantage of dispensing with the contactors for reversing alternate half-cycles. The series of positive half-cycles can be regarded as consisting of a steady d.c. component with an a.c. component superimposed. The motor windings can be arranged so that the m.m.f.'s produced by the d.c. components of the three phases cancel out, so that the overall effect is that due to the a.c. component. However, this a.c. component is very much less than that obtained with a true a.c. supply, so the output torque is considerably reduced. Tests also show that the speed of the motor when running in this manner oscillates about a mean value, because the alternating component of the current departs substantially from a sinusoidal waveform. For a constant-torque output, therefore, the angle of lag between the mechanical angle of the rotor and the supply-current vector

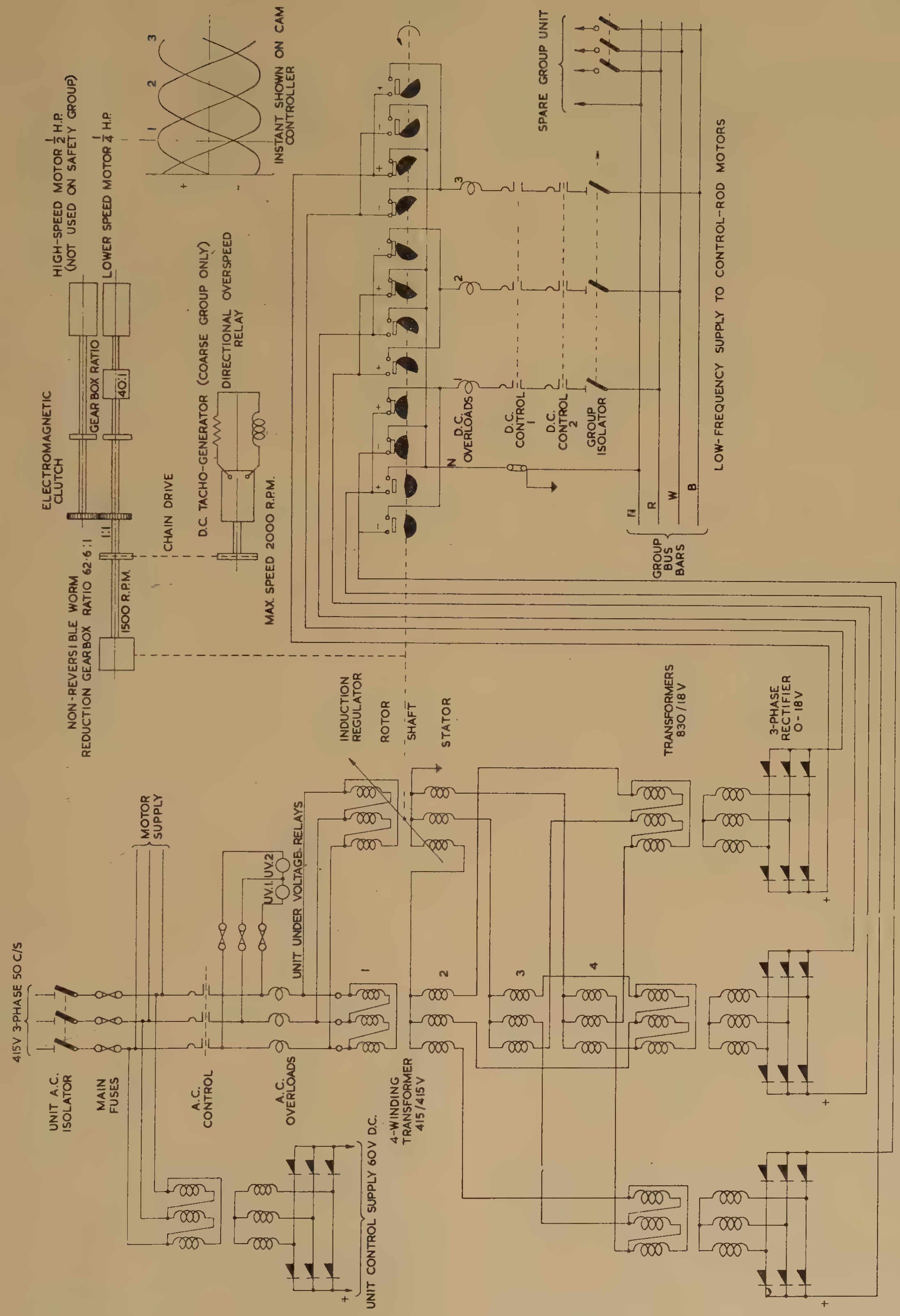


Fig. 9.—Schematic of low-frequency supply unit.

varies throughout the cycle. Owing to this difficulty and to the need for obtaining the maximum torque from a low-inertia machine, this scheme was rejected.

(6) CONCLUSIONS

Further experimental data and operating experience are required of insulating materials and components working in high radiation fields. This information would enable a better assessment to be made of the likely operating life of a component and would permit more economic design by the better use of materials.

Existing automatic control techniques are sufficiently reliable to enable plant working in radioactive areas to be remotely controlled. However, careful consideration must be given to the layout of the controls and indicating equipment to ensure that the operator has a complete understanding of what is taking place.

(7) ACKNOWLEDGMENTS

The authors wish to acknowledge the value of the discussions held with the Industrial Group of the United Kingdom Atomic Energy Authority during which certain features of the design philosophy were evolved.

Their thanks are also due to the engineers responsible for the design of the mechanical aspects of the plant, and to the General Electric Company, Limited, of England for permission to publish the paper.

(8) REFERENCES

(1) Sisman, O., and Bopp, C. D.: Oak Ridge National Laboratories, Report No. 938.
(2) Sisman, O., and Bopp, C. D.: Oak Ridge National Laboratories, Report No. 1373.
(3) Calkins, V. P.: 'Radiation Damage to Nonmetallic Materials', Chemical Engineering Process Symposium Series, No. 12, p. 28.
(4) Sisman, O., and Wilson, J. C.: 'Engineering Use of Damage Data', *Nucleonics*, September, 1956, **14**, p. 58.
(5) Harrington, R.: 'Damaging Effects of Radiation on Plastics and Elastomers', *ibid.*, p. 70.
(6) Cox, R. J., and Walker, J.: 'The Control of Nuclear Reactors', *Proceedings I.E.E.*, Paper No. 2068 M, March, 1956 (**103 B**, p. 577).
(7) Lockett, G. E.: 'Some Design Aspects of Nuclear-Reactor Control Mechanisms', *ibid.*, Paper No. 2046 M, March, 1956 (**103 B**, p. 597).

DISCUSSION BEFORE A MEETING OF THE SUPPLY SECTION HELD IN CONJUNCTION WITH THE BRITISH NUCLEAR ENERGY CONFERENCE, 28TH JANUARY, 1959

Mr. K. P. Gibbs: This subject can have a great effect on the availability and successful operation of the stations in the civil power programme. The design of the fuelling machine and other ancillaries is a field in which there are considerable variations between the views of the various consortia. The authors are to be congratulated on being among the first to see the necessity for on-load servicing of control-rod mechanisms and to develop equipment to carry out this function. Such a facility will be standard in all future stations. I feel that the paper has insufficiently emphasized the importance of simple and robust design, which is necessary for components which are difficult if not impossible to maintain. In particular, I have doubts whether the large number of wire ropes and pulleys shown on the cross-section of the reactor servicing machine will give the necessary freedom from trouble. In servicing control-rod mechanisms it is necessary, for the design described, to lower the control rod fully into the reactor core and then withdraw it; the same procedure will have to be carried out with the replacement control rod. The disturbances to reactor flux which this must produce are undesirable, and a scheme in which the rod did not have to be lowered into the reactor would be preferable.

I agree with the decision to locate the machine operator in a separate control room rather than on the machine. This leads to some difficulty in running the large number of control leads necessary between the control room and the machine, but it gives the operator better working conditions and greater freedom from hazard in the event of any unforeseen occurrence.

I think that the authors were correct to use some automatic or semi-automatic control for the fuelling machine, which carries out daily a completely repetitive operation. The operator can, in general, know that an operation is successful only by readings on dials and lights. These signals can as easily automatically initiate the next operation. The automatic control will not get tired at the end of a shift. I am not so sure of the argument for sequence control of the servicing machine. Although some of the operations are repetitive, the machine has many different duties and its very title suggests that one may frequently encounter the unexpected. In these circumstances, complete freedom of action within the limits of the preventative interlock mentioned is probably of greater value than the freedom from error given by the sequence control.

On the design of the control-rod drive units, I am rather doubtful about the decision to leave all the actuators connected in parallel during free fall. This implies that stiffness in a relatively few actuators might delay the insertion of all rods. It should be the aim to insert some rods into the reactor as rapidly as possible, and there appears to be little point in ensuring that all rods remain in step.

I note that it is estimated that the units will be available for maintenance only once a year, and will be interested to hear whether tests have been carried out on rope life under operational conditions of temperature and with the number of movements which may be expected in service.

Mr. P. R. Dunn: The paper indicates the novel problems arising in cables associated with reactors. Where exposure to radiation is not involved, the stress is on high temperature, and a variety of practical special-purpose cables has been produced using glass-fibres, p.v.c., p.t.f.e., silicone rubber, or asbestos as insulation. Under radiation, temporary changes in resistivity of insulants caused by ionization may not be significant, but the chemical effects of the γ-component lead to rapid deterioration of all organic materials.

Within the reactor, thermocouples installed or projected have nickel-chromium and nickel-aluminium as thermo-junctions and conductors, magnesium oxide as insulant and stainless steel as sheath. These are liable to long exposure to intense radiation and to temperatures up to 400° C. Their function is critical, but many of them cannot be replaced during the life of the reactor. The insulant and the sheath are among the most stable of materials for these conditions. More information on the stability of thermal e.m.f. of the couple materials is desirable, but all indications are that their low neutron-capture cross-section minimize instability arising from nuclear transmutations or radiation damage. Satisfactory operation is reported after doses exceeding 10^{21} neutrons/cm^2.

Cables for grab-head mechanisms may encounter frequen

short-term exposure to radiation and high temperature under extremely difficult mechanical conditions. It is generally possible to replace them, although the associated cost may be high. The choice of insulants is extremely restricted. Current attention is focused on fibres of alkali glass or fused silica which, in their necessarily dry or unimpregnated state, are not naturally well-adapted to the mechanical service required. Conductors are of nickel, stainless steel or thermo-couple materials. A number of cores, insulated with braided glass fibres, are laid up round a flexible pneumatic tube or a stainless-steel hawser, with a protective external braid of stainless-steel wires. Service life depends critically on design, and close collaboration between the cable-maker and the user is essential.

Mr. R. H. Kelsall: My comments refer to Section 5 of the paper. The combination motor and brake is of interest, owing to the absence of electrical contacts to control the braking. I should be interested to know where the peak of the torque/speed curve occurs relative to the 1 000 r.p.m. maximum speed. Such a design must be a compromise to ensure adequate torque under the full braking condition just before touch-down. If the motor rotor is permanently geared to the winding head, there is some risk of swarf becoming lodged in the air-gap, and great stress must be laid on cleanliness during assembly. A cylindrical rotor seems preferable.

Fig. 5 shows a conical winding drum similar to a fusee; it appears that the drum itself is unshrouded. Have the authors carried out drop tests to determine whether the rope springs out of the grooves of the winding drum at touch-down when tension is lost? The simplicity achieved is attractive when compared with the 4-year-old Calder Hall design. However, flexibility seems to have been sacrificed, since no easy adjustment of braking conditions exists. It might be helpful to compare the braking characteristics achieved with those of the Calder Hall mechanisms.

The authors' specification is similar to that at Calder Hall, where the specification called for an initial acceleration of 2 ft/sec^2 and a fall of 18 ft 6 in in less than 5 sec. The motor design at Calder Hall was determined largely by dimensional limitations and determined the gear ratio of 20 : 1. With this high ratio, the referred inertia was excessive and was disconnected by an electrically-operated clutch.

The bearing friction in Fig. 7 compares closely with that measured on the Calder Hall mechanisms, where a typical figure was 1–1½ lb-ft, being some 5% of the minimum torque available. The authors are using grease-packed bearings, whereas dry molybdenum disulphide was employed at Calder Hall.

The emergency-drop characteristics of a typical Calder Hall mechanism show that, for a 126 lb control rod, final braking occurs in under 5 sec and touch-down speed is 4½ in/sec. When the weight of the control rod was increased to 165½ lb, the characteristics were very similar in shape and the touch-down speed was still 4½ in/sec. This was achieved by adjustment of shims changing the air-gaps of the brake. There is, I think, some merit in flexibility being 'built in' to cater for changes being introduced later on.

Mr. H. K. Dent: I note with satisfaction that the authors have specified grease-packed bearings in the control mechanism. This, I am sure, is sound practice: the reliability of these components must be above suspicion. On the other hand, dry bearings are mentioned for the service machine. This is rather surprising, since the authors emphasized the need for reliability in these machines, and a breakdown would not necessarily be confined to the machine, but may require the complete plant to be shut down for maintenance, which might be difficult or even hazardous.

The Atomic Energy Authority has been pursuing this problem of lubrication. Oil lubrication is generally inconvenient, but grease appears to have wide application, and Table A lists proposed test schedules in this connection. These are not at the moment intended to form a manufacturing standard, but rather to provide guidance to the designer in the use of grease lubrication in radiation fields. Schedule 1 is intended for lubrication of control mechanisms, while schedule 2 specifies a greater radiation resistance and is intended for general use in such equipment as fuelling and service machines.

Table A

Irradiation Test Schedule for Greases

	Test Schedule 1	Test Schedule 2
Test 1	Drop point above 200° C at all doses up to 5 × 10^5 rad	Drop point above 250° C at all doses up to 1·5 × 10^9 rad
Test 2	Worked penetration between 220 and 300 at all doses up to 5 × 10^5 rad	Worked penetration between 200 and 300 at all doses up to 1·5 × 10^9 rad
Test 3	Loss by evaporation not to exceed a specified value	Loss by evaporation not to exceed a specified value
Test 4	Bearing-rig test. CO_2 atmosphere 150° C, 200 lb/in^2. Grease irradiated to 5 × 10^5 rad	Bearing-rig test. CO_2 atmosphere 200° C, 200 lb/in^2. Grease irradiated to 1·5 × 10^9 rad
Test 5	Test for compatibility with canning material	Test for compatibility with canning material

The first test limits the variation in melting point of the grease; the second ensures that the grease does not become unduly soft or (and this is of particular importance to control-rod mechanisms) so stiff as to cause undue stiction. The third test ensures there is no undue carry-over of lubricant by evaporation, and the fourth is designed to ensure that the grease remains stable and effective during its lifetime. Fig. A shows irradiation-induced changes in the worked penetration of a particular grease. Perhaps the authors would comment on their choice of dry lubrication in the service machine and indicate to what extent this may be reconsidered.

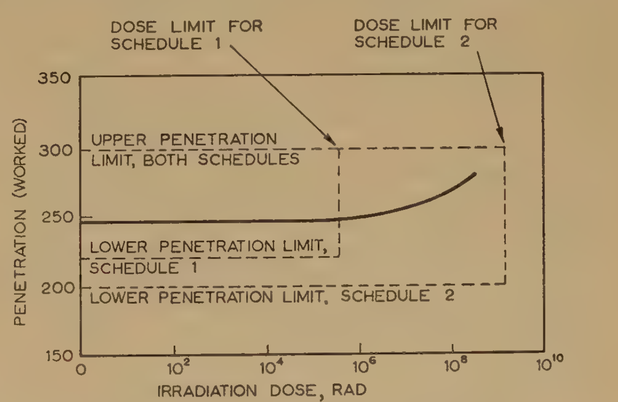


Fig. A.—Effect of irradiation on penetration.

Mr. W. R. Cox: Now that engineering principles must take radiation into account, difficulties are increased, but fortunately, mild steel—our great standby for structural purposes—is little affected by radiation. On the other hand, many of the most versatile insulating materials in common use are quickly ruled out. Plastics are being made with many varied and unusual properties. Is it possible that a plastic could be designed, which

is unaffected by radiation, has good insulating properties, is heat resistant and flexible?

The arguments put forward in favour of controlling the service machine from a suitably shielded and fixed control room seem to be very sound. It must be remembered that, even when travelling on the machine itself, the operator cannot actually see what he is doing and must still rely on the instruments provided. It would appear, however, that a control room common to both service-machine and charging-machine operators would be an advantage. In times of trouble these two operators must co-operate to clear some types of fault, and this would be much more easily accomplished if they were in the same control room.

Finally, a plea for simplicity. Some 40 years ago plant designed for almost every purpose was much simpler than it is to-day. Over the same period the reliability of individual components has improved considerably. This has resulted in the overall reliability factor for a composite piece of apparatus remaining about constant. If by simplification the number of components could be reduced, the reliability factor would improve considerably. Simplification is difficult, but it is an important criterion of good design, and the complications suggested during design discussions should not be added in the lighthearted way they very often are. Each complication not only adds to first cost, maintenance and testing costs, but tends to reduce overall reliability.

Mr. R. B. Quarmby: Clearly, in a paper of this kind, covering such a wide field, full explanations cannot always be given. One presumes that an undiscussed function of the servicing machine is to place a charge chute in the reactor and position it to serve a particular channel in the core, while a bottom charge chute is controlled from the charge-discharge machine. Fuel elements discharged into the servicing machine during an emergency would need much better shielding and cooling facilities than those provided for the control rods.

It is not clear what temperature is measured by the thermocouple shown in Fig. 5, or how the pressure seal of the lead is made. In connection with fuel elements having thermocouples attached, I should like to know how these are loaded and unloaded and whether they can be placed anywhere in a channel or just at the top.

The statement was made that one use of the television equipment is to look at the gas seal. I think just looking at a seal is not particularly helpful, and the real test is whether it lets the gas leak through. If television is used for internal viewing of the channels themselves, problems will arise in the provision of cooling and illumination facilities.

In the control mechanisms, the design should not allow the drum to overrun and wind the cable up in the reverse direction. Special care should also be given to ensure that high-speed motors are incapable of reversing and driving the control rods out at high speed.

The paper refers to reactor shut-down devices additional to the motor-controlled rods. I should like to know more about these and whether their dropping speeds are controlled.

Mr. D. J. E. Evans: The authors rightly stress the need for reliable equipment. In view of this and of the need to avoid shutting down the reactor unnecessarily, I presume that extensive testing of various completed assemblies has been undertaken to prove such items under conditions that approach as nearly as possible those to be met in practice. In order that we may obtain an appreciation of this work, would the authors give some idea of the facilities and time involved?

It is said that variable-frequency induction motors are proposed, because of their high reliability, for a power manipulator working in radioactive areas, and that the variable frequency is obtained from variable-speed inverter sets. What is the method of supply connection and duplication, if any, to ensure maximum overall reliability? How is the a.c. supply to the low-frequency supply units obtained and connected?

The authors state that the withdrawing and replacing of the control rods and their mechanisms for maintenance and repair can be carried out with the reactor on load. Later they suggest that units or mechanisms will normally be available for maintenance only once a year. What limits the availability of these units and what programme of maintenance is envisaged? Since it is expected that the gas surrounding these mechanisms will be at about 100° C, what is the life envisaged for the bearings, O-rings and motor of the control mechanisms?

In order to get a better appreciation of the schematic of low-frequency supply unit shown in Fig. 9, it is necessary to draw vector diagrams. From such diagrams it would appear that, to obtain the correct phasing at the group busbars, it is necessary for the output from the induction-regulator stator to lead the output from the secondaries of the four winding transformers, i.e. the mechnical rotor of the induction-regulator should rotate in the direction of the rotation of the magnetic field. Another conclusion is that the angle of lead should cover 720° for one revolution of the mechanical rotor, i.e. the induction regulator should be a 4-pole machine.

The authors state that there is reluctance to use fully automatic controls until more operational data are available. During the early days of operation, valuable experience will be obtained on the functioning of plant such as the servicing machine described in the paper. Has consideration been given to the incorporation of automatic facilities which could be used after initial operating experience has been obtained?

Mr. P. Balmer: Comparing the motor supply equipment with that installed at Calder Hall and Chapel Cross, the use of static, as opposed to continuously rotating, machinery for generating the holding and control voltage is to be preferred. At Calder Hall the fine regulation of reactor power can be done by hand-driven sine-potentiometers, i.e. a set of resistors fed by direct current and tapped to give an approximately sinusoidal 3-phase output when the brushgear is rotated on its faceplate. This system is essentially reliable and simple, but it has the drawback of dissipating power continuously.

The electrical interlocks at Calder Hall are particularly comprehensive, so that the change-over from one motor supply set to a standby set can be completed without dropping the rods in. A single 2-element voltmeter with 3-phase to 2-phase conversion was found to be valuable for paralleling. A set of d.c. moving-coil relays provided an automatic interlock. Do the authors expect to have to parallel two sets of induction regulators for this service?

Regarding the rod-actuating mechanism, the ideal control motor produces a torque proportional to displacement and hence tends to oscillate about a stable position. Damper bars on the rotor helped to prevent this at Calder Hall. Is it correct to assume that the high-resistance stator cage serves a similar purpose in the mechanism described in the paper?

Are all the rod-motor torques referred back to the induction-regulator shaft to be held by the irreversible worm? It has been found that irreversible worms tend to drive back under vibration conditions which drastically reduce the coefficient of friction, so that a back-up brake is required.

I understand that, to reduce thermal stresses in the reactor in the event of power-supply failure, it is desirable to hold the rods for a short period rather than drop them as in an emergency shut-down. Do the authors agree?

Finally, is it desirable or necessary to have a linear rod-position scale on the magslip receiver, in view of the fact that the invested reactivity of the rod follows a sine-squared law?

Mr. G. C. Olver: Great trouble has been experienced with rubbing carbon-to-metal contacts in dry atmospheres, such as are probable within a reactor pressure vessel. Can the authors tell us more about the slip-ring column?

A conical drum entails winding the rope more tightly over that part of its length which is most subject to changes of temperature. It must also be of greater diameter than a cylindrical drum to take the same length of rope. These factors make the task of the machine designer more difficult. Moreover, we have not yet got ropes which will give a satisfactory life, even in the easiest possible conditions.

By using a wound resistance across the motor terminals we can adapt the same motor for different rod weights and speeds simply by varying the resistance. Do not the authors feel that the extra flexibility so simply achieved is preferable to the rigidity of a high-resistance auxiliary cage winding?

We consider that it is unsafe to leave the rod motors connected to a busbar during a drop, since one rod sticking would slow up the rest. We also believe, as a result of tests, that it is safe to change from one supply to another by using a change-over break-before-make contactor.

Lastly we suggest that it is better to avoid the release of rope tension caused by allowing the rod to rest on its bottom stop in the fully 'home' position. Any form of rope-tension indicator would then tend to show a broken rope, which would give a false alarm to the reactor operator.

Mr. J. C. Williams: Electrical machines and devices have three major elements—conducting paths, insulation and magnetic circuits. Insulation difficulties and the need for conductors to be contained to avoid spreading undesirable contaminants into the reactor core have been described. Have the authors considered the stability of the conductors under high temperatures and irradiation conditions? Is there embrittlement of the conductor materials?

Magnetic circuits under reactor conditions have not been mentioned. Demagnetization of materials may occur at elevated temperatures and under mechanical shock. Neutron bombardment produces dislocations in materials, and it is possible that some demagnetization could occur. This matter is important, because the control-rod motors have permanent-magnet rotors. Little information is available on radiation effects on magnetic properties. Have the authors considered the problem, and are they satisfied that the permanent magnets they have chosen will have a 20-year life under reactor conditions? The literature suggests that, within a given series of magnetic alloys, the behaviour under irradiation conditions can vary widely with specific composition.

Can the authors give details of the circulators which propel the carbon-dioxide coolant in the charge-discharge machine?

The merits of automatic control should be related to operating techniques. If fuel shuffling is adopted—and there is doubt in some quarters whether fuel shuffling is economically or technically sound—there may be a case for automatic operation. If there is no fuel shuffling, the degree of use for these machines would be so limited that the automatic operation would be difficult to justify.

Lubrication has two main functions—to separate surfaces moving relative to each other and to dissipate heat. Do the authors feel that dry bearings dissipate heat adequately under the fairly high temperatures of nuclear equipment?

Mr. F. C. Walmsley: I should like to see mention of other materials in the very useful list of insulating materials and their gradings regarding the effects of radiation given in Section 2. I note that all ceramics have been classed as good, but mica-bonded glass could also be brought into that category, since it has been employed in the application indicated. Mica could also be included.

[The authors' reply to the above discussion will be found on p. 275.]

NORTH-WESTERN CENTRE AT MANCHESTER, 6TH JANUARY, 1959

Mr. W. J. Outram: I was a little disappointed to find that the paper dealt with only three particular items of electric-mechanical plant directly associated with the reactor in a base-load nuclear power station, and trust that this paper is only a forerunner of others dealing with other electrical-mechanical plant of reactors such as main gas circulator, duct valves, burst-fuel-element detecting equipment, etc. Any additional information the author can give on the charge machine would be most welcome, because as yet only a passing reference has been made to this particular item.

A philosophy has been adopted of fully remote operation using series-automatic and sequence techniques, thereby enabling the shielding to be reduced on the service and charge machines and permitting the use of semi-skilled operators. In view of the consequence of failure of this type of equipment—or, indeed, of any one part of it—I believe that a rather simpler approach, even with its incumbent increasing shielding and the use of rather more skilled operators, would have been preferable at this stage in the development of base-load nuclear power stations.

I agree that a static solution to the motor supply equipment for control-rod mechanisms is very desirable, but have not as yet met any really satisfactory solution to this problem; there is adequate scope for ingenuity and effort on this, although in itself it is not an 'in pile' auxiliary.

The paper refers to the emergency shut-down device using ceramic-insulated coils. Was any thought given to positioning these coils in locations remote from high temperatures and flux, working through some mechanical linkage, or was pneumatic operation using compressed carbon-dioxide considered? An approach in this form may well be necessary in some advanced types of reactors using much higher gas temperatures.

Mr. D. M. Sutherland: The paper succeeds in its aim to bring forward the special nature of problems encountered in design of reactor auxiliaries. It has extra interest when we reflect that the problems concern designs for nuclear power stations actually being constructed. It emphasizes the importance of the engineering aspects of these auxiliary units, involving much work in new and widely differing fields, and the authors rightly make it clear that extensive research and development programmes are essential to proper design progress. A further important aspect of this work which may not be generally appreciated is that the design of the auxiliary equipment must be complementary to the design of the reactor and the station as a whole. Size, weight, method of motivation, maintenance facilities and other features materially influence the layout of the plant, and must be carefully considered from the earliest stages of a station design concept. The machines are not simply separate items to work on or around a specified reactor—they are essentially integral portions of a complete station.

Lubrication is mentioned only in connection with control-rod mechanisms. The servicing and charge machines, with higher radiation and temperature levels, must be more difficult, and the lubrication measures adopted would be of interest.

Can the servicing machine described remove a control rod mechanism which has seized, or has broken its rod rope?

If the control-rod rope suffers a transient release when lowering, might it uncoil off the drum of the mechanism?

Have the authors considered the provision of a powered grab on the lower end of the television camera inserted by the servicing machine?

Mr. C. Ayers: In Section 2 the authors refer to the fact that there is no operational experience relating to insulating materials under the conditions obtaining in a power reactor. They also state that such experimental data that do exist have to be used with discretion. With an appreciation of the above state of affairs the authors give a Table of insulating materials roughly classified as good, fair and poor. Are these descriptions based on judicious reasoning applied to existing data, or on the author's own experimental work in this field? The authors appear to have selected insulants in the 'fair' classification for certain duties. Their reasoning behind this choice would be of interest, for I suspect that it is more profound than the limitation of the voltage to 110 volts and the flexibility of the material.

The authors refer in Section 4.5 to the fact that high-grade operators cannot be spared for routine driving of the charge and service machines. While I agree that, by adequate attention to the mode of operation and the consequences of failure, a successful marriage between automatic and manual control can be achieved, this should be done wisely and with full knowledge of the facts to avoid a separation or even a divorce. An entirely successful solution cannot be worked out in the design office, and mock-up testing is necessary to obtain the desired system, bearing in mind that such a machine has not yet operated in earnest.

While I share the optimism of the authors that the mechanisms described can be and will be made to operate under the conditions demanded by a reactor connected to the public electricity supply, I feel that the statement in the second paragraph of the Conclusions is a little premature. I trust, however, that my reserved judgment on these matters may be proved too conservative in a few years' time.

Mr. W. Macrae: In more established fields of engineering the methods of carrying out various operations are well known, as are the reasons for them. In nuclear power this stage has not been reached, and it is probably fair to say that the devices designed to fulfil a certain function will differ widely. There is a difference, not only in the designs, but in the philosophies behind them. Who is to say which approach is best? Only practical operation and experience will guide us. That is not to say that some present designs will not work satisfactorily, but that some may prove to be more convenient to operate or require less maintenance than others.

While there is a need for radiation-resistant greases for special applications, there are more applications for greases which are stable and will maintain their lubricating properties over long periods: their radiation resistance is of secondary importance.

The radiation level outside the servicing machine is quoted as 10 mr/h under the worst conditions. This seems very low for a virtual unshielded machine, bearing in mind the scattering of the neutron beam which must occur when it impinges on components in the machine.

The time for withdrawing a control rod from the core during servicing is quoted as 3 min. This would produce a relatively high rate of change of reactivity and could cause trouble with the reactor power control. Withdrawal in perhaps 10–15 min would probably be safer.

Mr. A. E. Green: Comparing the design of the control-rod mechanism with that used at Calder Hall, it is interesting to note that the electromagnetic clutch has been eliminated and the role of the eddy-current brake is being performed by back-driving the motor under controlled conditions. However, it would appear that special precautions would be necessary to ensure that the hoist rope winds reliably on the conical winding drum. Would the authors describe how they cater for loss of rope tension and the possibility of ropes which may deteriorate in condition after a period of service?

It would be useful to know the type of lubrication being employed for the bearings and gearing in the control-rod mechanisms. Have the authors obtained any indications of large changes in the coefficients of friction when life-testing mechanisms in a simulated reactor carbon-dioxide atmosphere where the oxygen impurity and water content may each be less than the order of 0·01%?

With reference to the low-frequency supply unit, I agree with the authors' philosophy of having a static system as far as possible so as to enhance reliability. Would the authors give further details of the arrangements of the cam-operated switching contacts, since I feel that this feature may tend to lessen reliability?

[The authors' reply to the above discussion will be found on the next page.]

NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 9TH MARCH, 1959

Mr. J. W. Bayles: Section 6 stresses the need for operating experience before the proposed designs can be correctly assessed. The engineers are producing various designs, but operating experience in power stations will not be obtained for some time yet, when it should provide valuable data for future development.

In connection with Sections 2 and 3 it should be remembered that materials and surface treatments may have to withstand, not only operating conditions, but also quite severe conditions in commissioning. For example, control-rod mechanisms may be positioned in a reactor for months before the coolant gas is introduced; they may thus be subjected to damp atmospheric conditions, conditions arising during graphite drying, and then to operating conditions.

Section 4 brings out the large number of operations in sequence needed to replace one rod-mechanism, and the serious consequences of a failure during such a sequence, while in Section 5.1 it is pointed out that the highest possible reliability is required in control-rod mechanisms, since they will normally be available for maintenance only once a year. Do we conclude from these considerations that servicing under load is an operation only to be undertaken very occasionally, and that normal maintenance of control-rod mechanisms will be left to annual shut-down maintenance periods?

The control-rod mechanism shown in Fig. 5 has a conical winding-drum, rope suspension and permanent-magnet rotor. The conical winding-drum helps to provide satisfactory dynamic characteristics during emergency shut-down, and to that extent is a good feature. The rope is a doubtful feature; experience shows that difficulties arise due to tendencies to unwind and stretch, and breakages can be very difficult. Ropes will probably be even less suitable at higher temperatures.

The permanent-magnet rotor imposes considerable limitation in working voltage of the hoist motor; faster insertion speeds would increase this limitation. What voltages would be induced in the hoist-motor windings if they were connected during free fall to arrest the control rods at some point? It also seems disadvantageous that a winding fault may greatly increase the time of rod insertion. What advantage is claimed for the synchronizing effect between control-rod motors during free fall? It would appear that independent action is most desirable.

Fig. 9 shows an interesting scheme for a low-frequency supply unit. There are, of course, other schemes available, and no doubt all will be engineered for maximum reliability, so it would seem that economics and operational features may eventually influence the choice. The scheme illustrated has some movable parts and will require maintenance; spare plant is provided for. There are many component parts, and the overall rating of the components seems generous for the output obtainable.

The scheme shown in Fig. 9 would not appear to have any special advantage of continuity of control when spare plant is required to assume load automatically from operational plant due to any fault which temporarily lowers output voltage. Presumably the control rods drop a certain amount during the rapid switch-over.

Mr. E. J. M. Marrian: There seems no worth-while advantage in having access to the reactor core from both top and bottom, since it involves additional machinery, possibly additional personnel and certainly increased height of the reactor building. I should therefore like to know why this arrangement was adopted. The authors mention that fuel elements, with thermocouples attached, are inserted from the top, while normal fuel charging and discharging takes place from the bottom. Is there access to every fuel channel from the top?

It is evident from Fig. 5 that some improvement has been effected in the design of the control-rod mechanisms compared with those in use at Calder Hall and Chapel Cross. The use of a conical drum is a very good idea, although I cannot see how the rope is prevented from leaving the groove when the rod bottoms. The use of a permanent-magnet rotor in the operating motor may be some disadvantage. Apart from the over-voltage hazard during emergency shut-downs, the jamming of one motor may retard the dropping of all the rods unless steps are taken to disconnect all the motors individually. Fig. 5 does not make it clear how the magslip transmitter is driven; if it is from the drum, the receiver dials must have non-linear scales, which would adversely affect the accurate control of rod position.

The low-frequency supply unit is interesting, although I wonder whether, in the long run, continuously rotating machines may not be more reliable than the rectifiers and cam-operated contacts which replace them. I would welcome information on how the fine control rods are operated as distinct from the main group of coarse-control or safety rods.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. A. E. Harwood, P. Scott and **B. H. Stonehouse** (*in reply*): We have decided to reply on a subject basis rather than to individuals.

Mr. Sutherland very rightly states that the design of the auxiliary equipment for a power reactor must be carefully integrated with the principal components at all stages of design. Although the auxiliary equipment, such as charge machines, may appear complex when viewed as a whole, the individual machine components are kept essentially simple and robust. This is vital if the high degree of reliability necessary is to be obtained. This reliability must be proved by extensive testing on prototype vital components and followed by factory proving tests lasting several months of a complete machine.

Mica and glass-bonded mica withstand radiation conditions well. Almost all inorganic, non-fissile materials will withstand a considerable radiation dose without serious change in physical properties. Field tests have been carried out, in co-operation with the Atomic Energy Research Establishment, on polythene- and p.v.c.-insulated cables. A great deal of general information on radiation damage is given in the paper references.

The slip-ring column shown in the paper was for work in air of normal atmospheric moisture content, and no serious wear problems were experienced.

The advantages of having top and bottom access to the core and using the bottom access for fuel-element charge and discharge are principally operational; they are:

(*a*) The fuel element need not be preheated before charging so as to avoid violent temperature transients as it passes through the hot gas at the top of the reactor.

(*b*) The charge-machine mechanisms work at gas-inlet temperature.

(*c*) Gravity assists in the discharge of the fuel, which may be handled a complete channel at a time.

(*d*) The top control face of the reactor is kept relatively free from radioactive material, and there is no need to disturb the control mechanisms during charging.

(*e*) The facilities to carry out operations at both ends of a faulty channel may be most valuable.

(*f*) The charge machine may be readily removed from the vault and common decontamination and maintenance facilities used for several reactors on a station.

We welcome Mr. Dent's contribution on grease lubrication. The increasing availability of greases for use in hot carbon dioxide is resulting in many drives in the replacement of dry bearings with grease-packed ball races. The heat dissipation in dry bearings is kept low by using low-pressure loadings and speeds.

In the service machine, wire ropes were used for actuating some of the mechanisms in preference to gears and lead-screws, since this resulted in a simpler mechanism inside the pressure vessel which is considered to be quite as reliable as the alternative arrangement.

Double O-rings are used to seal the standpipe caps and leak-detection equipment provided, so that the proper seating of the cap may be checked before the machine is removed.

The reactor television cameras, which are cooled to 50°C by an external supply of cold carbon dioxide, are fitted with power-operated grabs.

Sequence control is used only to a very limited extent in the service machine, and random mechanism operations are possible on both machines. The control-gear design permits sequence changes and allows for increases in possible automatic operations if these become desirable.

Three guides ensure that the rope remains in the grooves of the control-rod-mechanism conical winding drum. A relaxation in the required accuracy of control-rod position indication has permitted a change to a pancake winding drum. The rope which is wound on to the largest drum diameter has been at the highest operating temperature. The machine is assembled under clean conditions with the magnets unenergized.

On-load servicing of the control-rod mechanisms will take place regularly. The frequency of maintenance is determined by the life of the seal O-rings, bearings and rope. The majority of the mechanisms will be maintained annually. The service machine can extract and replace mechanisms at three times this rate.

The control-rod position-synchro transmitter is geared directly to the winding drum. The resulting non-linear scale of the position indicator is not a serious disadvantage, since the reactivity/distance relationship is also non-linear.

The lack of flexibility of the high-resistance cage controlling the braking of the control-rod mechanism is not serious, since changes in control-rod weights are rare. This arrangement is preferable to using shunt resistances at the stator terminals. However, this less reliable arrangement, although wasteful in power, can be used if increases are made to control-rod weight after motor manufacture is complete.

*

We agree that the number of motors electrically coupled during an emergency shut-down should be kept small. However, this arrangement is preferable to the alternatives of using a separate braking system and either declutching the motor or using a separately-excited machine rotor.

The development of a wholly static low-frequency generating unit is desirable, especially for automatically controlled units. Two l.f. supply units are readily synchronized, since currents do not circulate between units unless the synchronizing is exceptionally bad. The maximum amount of reactivity lost during an automatic change-over to a standby low-frequency supply unit is $3 \cdot 5 \times 10^{-4} K$, which may be automatically compensated.

DISCUSSION ON 'THE DIGITAL COMPUTER APPLIED TO THE DESIGN OF LARGE POWER TRANSFORMERS'*

Before the NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER *28th January, and the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *4th March*, 1958.

Mr. H. W. Hardern (*at Manchester*): A computer can be of assistance to transformer designers in three ways, namely

(*a*) To determine the leading dimensions of a preliminary design having required optimum features, such as might be required for tendering purposes, without going into too much detailed work.

(*b*) To calculate in detail some features of a final design where human calculation may be tedious and time-consuming, such as the determination of mechanical forces or stresses under impulse voltages.

(*c*) Preparation of final detailed designs for manufacturing purposes.

The possibility of the first two of these is already with us, but much involved programming is required for the third, and this may for the present be beyond our reach, except for simple cases.

When comparing the time taken by manual design and by use of computer it is necessary to take into account the times required for programming, for translation of the computer output into everyday language understood by the drawing office and the workman, and also any time which may be found necessary to check and adjust the computered design. Finally, we must ensure that designs made using a computer do not have that indefinable difference between the tailor-made suit and one bought 'off the peg'.

Mr. H. L. Thomas (*at Manchester*): Transformer design as generally practised commercially has always meant a trial-and-error process of arriving at suitable proportions and arrangements of windings and core such that their inherent physical and electrical characteristics are as close as possible to specified guaranteed values or to optimum values consistent with minimum cost. I can emphasize from experience that the really difficult part of the job is finding the best sizes and arrangements of strands, turns, ducts, etc., to produce windings which will fit into preconceived proportions to yield the right results, bearing in mind that there are many possible adjustable parameters and many dependent variables involved. This is where the digital computer, with its logical facilities and great speed of operation, can be of real help, although considerable knowledge, skill and ingenuity are required in the initial preparation of a programme of instructions to achieve this object. A most valuable prerequisite of this is that it enforces a critical re-examination of existing design processes, since it now becomes essential for every possible eventuality to be foreseen and catered for by explicit instructions in the programme.

I know of a programme which was developed on rather different lines from that described in the paper, following closely the usual processes adopted by a designer and using a scheme of convergence centred around the reactance. It is interesting to compare the times taken on the same machine to produce ten different designs using this programme with the figures quoted for seven designs in Section 6.3 of the paper. The average time taken for all inputs and computations is 90 sec per design as compared with 102 sec from the authors' Table—which is quite remarkable agreement. A valuable application of a computer design programme is its facility for producing rapidly a large range of alternatives for analytical purposes. Figs. B and C

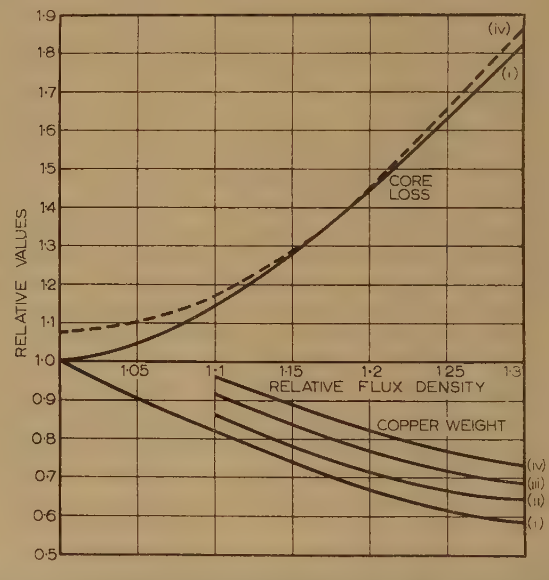


Fig. B.—Core loss and copper weight relative to flux density.

Transformer data: 10 MVA, 33/66 kV, delta tertiary, + 5 and − 15% h.v. tappings 9·5% reactance, fixed core area.

(i) 72 kW. (ii) 68 kW. (iii) 64 kW. (iv) 60 kW.

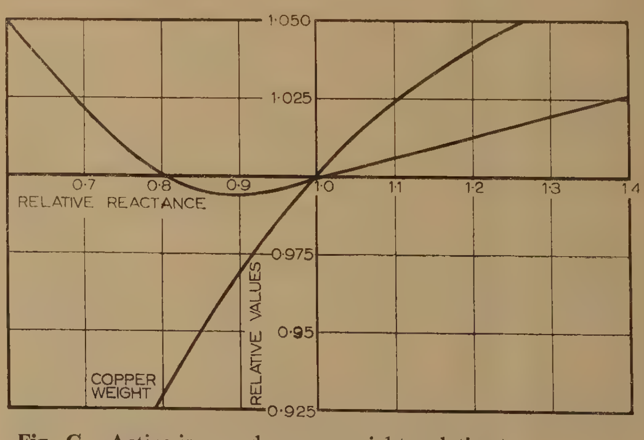


Fig. C.—Active iron and copper weights relative to reactance. Transformer data as in Fig. B.

* SHARPLEY, W. A., and OLDFIELD, J. V.: Paper No. 2404 S, August, 1957 (see 105 A, p. 112).

illustrate some typical relationships obtained from the analysis of some 80 designs produced by the computer.

Mr. R. S. Mamak (*at Manchester*): Because there are more equations than independent variables for a given specification, there is more than one set of parameters which will satisfy the requirements. Fortunately, owing to standardization considerations, not all the independent variables are continuous. For example, the core area and core centres may have to satisfy certain discrete values, and the only continuous variables left are flux density, window height and copper area. Under these circumstances the excellent iterative procedure given in the paper is believed to be too elaborate and an alternative technique is suggested for consideration.

The essential basis of the technique is the separate design of the core and windings, with the impedance and cost equations providing the necessary mutual restrictions. To illustrate the technique, the design of the copper windings will be briefly sketched. The necessary conditions to be satisfied are:

(*a*) Copper loss must equal the specified figure, i.e.

$$\frac{I_1^2 l_1}{A_1} + \frac{I_2^2 l_2}{A_2} = K_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(A)}$$

(*b*) Weight of copper, for given core area and flux density, must be a minimum, i.e.

$$w = K_2(l_1A_1 + l_2A_2) \quad . \quad . \quad . \quad . \quad . \quad \text{(B)}$$

From eqns. (A) and (B), and remembering that, to a first approximation, $dl_1/dA_1 = dl_2/dA_2 = 0$, a quadratic equation is obtained for condition (*b*), i.e. $dw/dA_1 = 0$. The determination of the roots of a quadratic equation is a standard process, and consequently the optimum copper areas are immediately obtained.

The assumptions made in formulating the 'incremental' equations (9)–(11) in the paper inherently require an initial estimate of, at the worst, about 20% error, with the consequent necessity for a design engineer. Essentially the difficulty arises because one is linearizing a non-linear problem. To overcome this a statistical iterative technique (it entailed the judicious selection of constants) was used in References 1 and 4, and was claimed to give converging results even when the initial parameters were as much as 45% in error. Why have the authors deliberately used an analytic approach, and thus introduced this inherent 'within limits' obstacle?

Mr. K. S. Rowe (*at Manchester*): If one has a transformer of given rating and voltage class to design, the loss and reactance being stipulated, the design can be completed on several core sizes, the range of which is governed by practical considerations. In general, the cheapest non-capitalized design on any particular core size is obtained by using the maximum permissible flux density.

Fig. A (my contribution to the discussion at London) shows how the cost varies with core area. Since the flux density is fixed, the curve of iron weight can also represent iron loss. It can be seen that the cheapest design appears when the relative iron loss is 1·08. With the authors' method of approach and a relative iron loss of 1·2, the resultant design would have cost more. Thus, how do the authors know what iron loss to use in order to produce the cheapest design? In my opinion this is of prime importance at the quotation stage.

A great deal of the paper is given to emphasizing the convergence routine, and very little has been said about how the core proportions change at various stages in the convergence process to allow space for the windings to be formed, i.e. the block labelled 'compute basic design routine' in Fig. 1. From an analysis of the core diameters, flux densities and iron losses given in Table 2 and Figs. 6 and 7, it appears as if the leg length was fixed throughout. Was this so? If it was, there is only one possible solution of core diameter, flux and current densities to meet the guaranteed values of iron loss, load loss and reactance, provided that the high-to-low clearance is fixed—which, in fact, it is.

Mr. J. C. Gladman (*at Manchester*): I agree that there is considerable scope for the improvement of the design programme by the inclusion of sub-routines for calculating more detailed design information, but the length of these routines will probably make them uneconomical until one of the faster computers now becoming available can be used. The design method must also be extended to allow automatic minimization of manufacturing costs within the limits of size, weight and other considerations which may be imposed by a particular specification. There is a danger that such a comprehensive design routine might cause the design engineer to lose touch with the kind of transformer which is being designed if adequate supervision of the routine is not provided. The routine may also become unnecessarily complicated and lengthy by the inclusion of too many sub-routines in the major iterative loop.

It is therefore suggested that future development of the programme should lead to a design routine divided into two principal parts. The first should give rapid convergence to an optimum or near-optimum design, using a fairly simple routine and printing occasional checks on the computation. The more detailed design and manufacturing data could then be calculated for one or two designs near the optimum, leaving the final choice of design to the experience of the design engineer.

Mr. B. Birtwistle (*at Manchester*): The design process described by the authors would appear to depend to a large extent on the method adopted to secure automatic convergence to the desired characteristics. This method requires that certain of the initial data needed by the programme for each design run must be provided from preliminary calculations by a competent design engineer. In other words, the computer is mainly being used for final adjustment of manually-drafted designs. The alternative approach seems preferable, whereby the computer, given the customer's requirements only as initial data, produces a design which is then finally adjusted by the design engineer. This is the approach we have used with regard to the computer design of various electrical plant with some success. For example, a programme for the design of d.c. motors requires only five numbers, representing the required power, upper and lower speeds, voltage and excitation voltage, to be fed into the computer to initiate the design process. Why did the authors choose their particular method?

It would appear that considerable analysis of various transformer designs is necessary to obtain eqns. (2)–(4), from which the convergence criteria are derived. It would also appear that these criteria would be insensitive to the numerical value of the indices over quite a wide range. Have the authors any further information on these points?

The authors rejected the use of interpretive floating-point routines, which would have enabled them to write and develop their programmes with less effort than is otherwise required on a fixed-point machine. Surely the saving in programming effort is worth while in development work of this type, even at the expense of extra machine time.

Mr. M. A. Spurway (*at Manchester*): The coefficient f_b relates iron loss and flux density and may have a value between 2 and 5 (Section 5.1). The coefficient f_j relates iron loss and current density. For a given current, the current density may be varied by increasing the dimension of the conductor axially, radially or in both directions simultaneously, which suggests that f_j, also, may have alternative values. Do the coefficients depend on the particular design being computed? If so, how is the appropriate set of values selected, and to what extent does the

designer need to anticipate the final design with regard to this selection? Alternatively, if only one value of each coefficient (excluding f_b) is used, how is f_j fixed? Can the indices be made sufficiently general to cover designs having a wide range of characteristics and design proportions, and ensure that the programme will always produce a design which is a practical one?

Fig. 8 shows the number of iterations for 52 designs, but does not indicate the range of characteristics and proportions covered.

Mr. D. F. Binns (*at Manchester*): The digital computer when used for the design of transformers has often been referred to as an electronic slide-rule. This emphasizes that each process of calculation needs an accuracy of only one part in a thousand, and the printing out of interim figures and final answers requires only four significant figures. This suggests a possible saving in computer time compared with more conventional computer work to high precision. Would the authors indicate what advantage can be taken of this fact in the computer used, and give their views on whether a computer is now economical for transformer design, weighing cost of machine time and programming against the cost, in engineers' time, of slide-rule calculations?

Professor M. G. Say (*at Edinburgh*): It has been suggested—perhaps by those who interpret literally the catch-phrase 'electronic brain'—that before long a computer will be able to furnish a complete design without any help from the designer. This is fallacy. The genius, if any, built into or used by a computer is of human origin, and the intelligence of printed answers can never exceed the ingenuity and experience of the designer who asks the question. Moreover, the questions are themselves often very difficult to formulate.

Used with understanding, a computer can make the designer more effective, more certain, and perhaps also more enterprising. Design has always been a field of so-called 'inspired guesswork', and its methods have often been (and may in some directions remain) empiric. This has sometimes been due to the sheer labour of elucidating anything like a rigid solution to a given problem. Consider core loss. Test data taken under controlled conditions are applied to built cores which differ significantly from test rings. Rounded off, multiplied by empirical factors to blanket the effects of joints, lateral flux-paths, grain orientation and non-uniform flux distribution, core-loss estimates are largely statistical. The all-important flux distribution in the core is no more than guessed at, and a computer programmed to evaluate such a distribution might produce results significant enough to suggest modifications in conventional core construction. The computer does the labour while the designer, his 'inspired guesswork' now firmly based, turns his attention to still more intricate physical problems.

The programme of computation here followed concentrates on the core and winding design, the losses, the reactance and the cost. The initial instructions to the computer require the parametric spread to be reasonably narrow: in fact, a preliminary hand design is necessary for a start, in order to economize in costly computer time. No doubt there will also be a considerable reduction in the number of data to be stored.

No attention is given in the programme to some important characteristics, such as impulse-voltage distribution and mechanical forces. (These would presumably be susceptible to separate calculation on a different programme.) Is it found that the two characteristics mentioned present no difficulty once the optimum design (which ignores them) has been computed?

I take it that, at the end of each iteration, the computer must calculate at least nine equations represented by the example of eqn. (12), as well as others concerned with core-plate sizes and conductor dimensions, before proceeding to the iteration. Much of the designer's insight must, I think, lie in the formulation of eqns. (2)–(8). What would be a typical numerical value for the exponent f_j in eqn. (3)? Although there is clearly a relation between core loss and the flux density and core diameter, that between core loss and current density is less obvious. I would expect the relation given in eqn. (8) to be rather a complicated one: it would be of interest to know how X is affected by D, B and J.

Mr. G. R. Small (*at Edinburgh*): A colleague and I have just completed a synchronous machine programme in which we made use of many of the organization sub-routines developed by the authors and found them readily adaptable to rotating machines. We have therefore found it very interesting to compare their paper with our programme. We found a marked similarity in the calculation of the bare copper size, even to the necessity for checking for negative dimensions. However, to avoid flimsy or square-section copper—both equally objectionable—we put limits on the width-to-depth ratio.

We took the view that it would be an experienced designer who would give the input, and it was therefore unnecessary for the programmer to allow for the ridiculous. However, given reasonable input, the programme should be such that a design would always be produced without the programme coming to a stop or requiring the intervention of the operator. From Fig. 5 and the text it would appear that the authors have allowed for operator intervention, which means that he must be an experienced designer as well. This surely cuts right across one of the great attractions of the computer for design work, namely that it relieves the designer of routine calculations. From our experience it would be asking too much for an experienced designer to become a highly skilled computer operator as well.

We gather that the programme does not necessarily produce the cheapest transformer. From Fig. 9 it would appear that three or four different designs can be produced, all meeting the required specification, and a manual selection is then carried out. Even so, only material costs appear to have been taken into account. What of labour costs? Or is it still the case with transformers that the design which uses the minimum amount of material is the cheapest? This is certainly not true of synchronous machines, so that, when writing our programme, both material and labour costs had to be considered. To achieve this we had to change our design philosophy, but we are now confident that, when we obtain a design, it is the cheapest machine possible both with regard to material and labour within the limits of the input, i.e. the cheapest machine within the limits of the designers' knowledge and experience.

The maximum amount of input possible was written into the programme to accelerate getting a design on to the computer and to reduce the possibility of input errors to a minimum. Does the programme, for example, work from tables of voltage ranges or does each voltage range require a long series of input items? From our experience so far we would say that an experienced designer could give an input within $\pm 10\%$, which would give a design requiring a reasonable number of iterations. On one or two occasions it has taken up to $3\frac{3}{4}$ min to complete, and it would appear from Fig. 8 that the authors have had a similar experience with two designs which have taken $4\frac{1}{2}$ min. Could the authors say whether on these two occasions the number of iterations were due to input being so far out or to awkwardness of the design? In our case this seemingly excessive time was due merely to the awkwardness of the design tackled.

621.313.333 : 621.316.719

The Institution of Electrical Engineers
Paper No. 2865 U
June 1959

DYNAMIC BRAKING OF 3-PHASE MOTORS BY CAPACITORS

By Professor T. V. SREENIVASAN, B.E., M.Sc.Tech.

(*The paper was first received* 22*nd September, and in revised form* 29*th December*, 1958.)

SUMMARY

When a series capacitor is introduced in one of the supply lines of a 3-phase induction motor working under normal load conditions, the torque developed by the motor is considerably reduced. If the speed falls below a certain value, the machine develops braking torque and decelerates to standstill and may even run in the opposite direction. This aspect was touched upon in a previous paper[1] and is now investigated further, both theoretically and experimentally. Applying the method of symmetrical components, the current and torque equations are obtained for the machine during the braking period. It is suggested that the driving torque developed by the machine at high speeds, even with the introduction of the series capacitor, can be avoided either by working the machine as a self-excited induction generator or by introducing a suitable series reactor in another supply line. These methods of dynamic braking are compared with the conventional plugging method.

LIST OF SYMBOLS

V_1, $V_1\angle 240°$, $V_1\angle 120°$ = Line voltages.
I_1, I_2, I_3 = Line currents.
I_a, I_b, I_c = Phase currents.
V_p, V_n = Positive and negative sequence components respectively of the voltage applied to the windings.
I_p, I_n = Positive and negative-sequence components respectively of the stator phase currents.
I_{2p}, I_{2n} = Positive- and negative-sequence components respectively of the rotor phase currents.
Z_p, Z_n = Impedance of the motor per phase, to positive- and negative sequence currents respectively.
Z_c = Capacitive reactance introduced in one line.
Z_r = Inductive reactance introduced in another line.

(1) INTRODUCTION

Dynamic braking of 3-phase induction motors is usually carried out either by plugging, or by injecting direct current into the stator windings after disconnecting the supply. In the first method, two of the supply leads to the motor are interchanged, with the result that the motor develops braking torque. The large current drawn from the mains, with resulting high energy loss, and the heavy-duty switching contacts required, are some of the obvious disadvantages of this method. With d.c. injection, a separate source of d.c. power is required and the low braking torque at low speeds may not be satisfactory.

If the voltages applied to the terminals of a polyphase motor are unbalanced, the unbalanced currents drawn by the motor can be resolved into a set of balanced positive-sequence components and another set of balanced negative-sequence components. The former exerts a torque in the positive direction (direction of rotation) and the latter, in the negative direction. In fact, this method of reducing the torque developed by a motor during the accelerating period, to control the acceleration, is adopted in the Kusa* method of starting. A single-phase reactor is introduced in one of the 3-phase supply lines, thereby causing unbalanced voltages to be impressed on the motor terminals. Thus, if there is no asymmetry in the circuit, the current drawn is completely of positive sequence; if asymmetry is caused by the introduction of a single-phase impedance, the current consists of both positive-sequence and negative-sequence components, and if there is no asymmetry but two leads are interchanged (plugging), the current is completely of negative sequence. Considering the case when asymmetry is caused by the introduction of a single-phase impedance, the magnitudes of the positive- and negative-sequence components, the torque exerted by them, and the net torque developed by the motor depend upon the value of the impedance and the speed of the motor. If a reactor is used, the negative-sequence component will always be less than the positive-sequence component and the motor will always develop driving torque. If an infinite reactor is used (one line open) the negative- and positive-sequence components of current are equal, but the motor still develops driving torque. If a capacitor is used, the negative-sequence component is greater than the positive-sequence component; but the net torque developed by the machine may be either driving torque or braking torque, depending upon the speed of the machine. This indicates a method of dynamic braking of induction motors, and forms the subject of the paper. For the purposes of calculation and test, a normal commercial 3 h.p., 400 volt, 50 c/s, 1 440 r.p.m., 3-phase delta-connected squirrel-cage motor, which was available, was chosen. Its measured constants were $Z_m = 35 + j418$, $Z_1 = 8\cdot 28 + j20$, $Z_2 = 10\cdot 1 + j20$, where Z_m is the magnetizing impedance, and Z_1 and Z_2 are the leakage impedance of the stator and rotor windings.

(2) CURRENT AND TORQUE EQUATIONS

(2.1) The General Equation

For a delta-connected motor (Fig. 1), considering the general case of three series impedances Z_c, Z_r and Z_x in the supply lines, the following equations are derived in Section 10:

$$I_p = \frac{V_1(Z_n + Z_c + Z_r + Z_x)}{Z_pZ_n + (Z_p + Z_n)(Z_c + Z_r + Z_x) + 3(Z_cZ_r + Z_rZ_x + Z_xZ_c)} \quad . \quad . \quad . \quad . \quad (1)$$

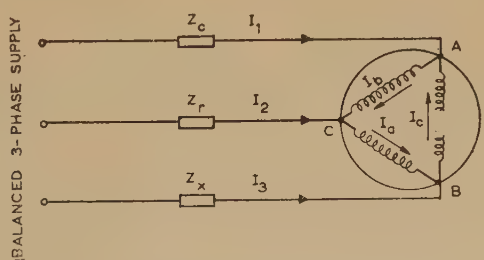


Fig. 1.—Pertaining to the general equation.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Prof. Sreenivasan is Assistant Professor at the Indian Institute of Technology, Kharagpur, India.

* *Kurzschlussläufersanftanlauf* = Short-circuited-rotor smooth starting.

$$I_n = \frac{V_1(Z_c + Z_r\angle 240^\circ + Z_x\angle 120^\circ)}{Z_pZ_n + (Z_p + Z_n)(Z_c + Z_r + Z_x) + 3(Z_cZ_r + Z_rZ_x + Z_xZ_c)} \quad . \quad . \quad . \quad . \quad (2)$$

$$I_{2p} = I_p\frac{Z_m}{Z_m + \dfrac{R_2}{S} + jx_2} \quad . \quad . \quad . \quad . \quad (3)$$

$$I_{2n} = I_n\frac{Z_m}{Z_m + \dfrac{R_2'}{2 - S} + jx_2} \quad . \quad . \quad . \quad . \quad (4)$$

R_2' is the rotor resistance to the negative-sequence component of rotor currents. In the numerical calculations it is assumed to be equal to R_2.

Hence, torque in synchronous watts at any slip S is given by

$$3I_{2p}^2\frac{R_2}{S} - 3I_{2n}^2\frac{R_2'}{2 - S} \quad . \quad . \quad . \quad . \quad (5)$$

(2.2) Capacitor Braking

If a capacitor Z_c only is used in one of the lines (Fig. 2), putting $Z_r = 0$ and $Z_x = 0$ in eqns. (1) and (2) gives

$$I_p = \frac{V_1(Z_n + Z_c)}{Z_pZ_n + (Z_p + Z_n)Z_c}$$

$$I_n = \frac{V_1Z_c}{Z_pZ_n + (Z_p + Z_n)Z_c}$$

$$I_a = \frac{V_1(Z_n + 2Z_c)}{Z_pZ_n + (Z_p + Z_n)Z_c}$$

$$I_b = \frac{V_1(Z_n + Z_c\angle 60^\circ)\angle 240^\circ}{Z_pZ_n + (Z_p + Z_n)Z_c}$$

$$I_c = \frac{V_1(Z_n + Z_c\angle 60^\circ)\angle 120^\circ}{Z_pZ_n + (Z_p + Z_n)Z_c}$$

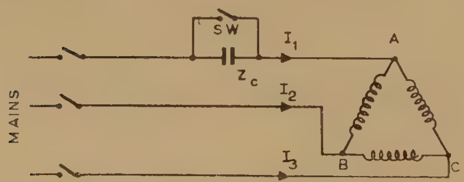


Fig. 2.—Capacitor braking.
SW open during braking period.

Similar expressions can be obtained for the line currents. Fig. 3 gives the loci of I_p and I_n, and Fig. 4, those of I_a, I_b and I_c. Only the locus of I_n is a circle, the others being bicircular quartics.

(2.3) Capacitor-Reactor Braking

If a capacitor, Z_c, is introduced in one line (Fig. 5) and a reactor, Z_r, in another line, by making appropriate substitutions in eqns. (1) and (2) and by putting $Z_x = 0$, I_p, I_n and the speed/torque characteristic can be calculated as in the previous case. Fig. 6 gives the loci of the phase currents.

A graphical construction for I_p, I_n and torque in terms of the corresponding quantities under balanced conditions may also be adopted for capacitor braking as described in Reference 1. When the graphical method is extended to cover capacitor-reactor braking, it becomes too involved to be of practical use.

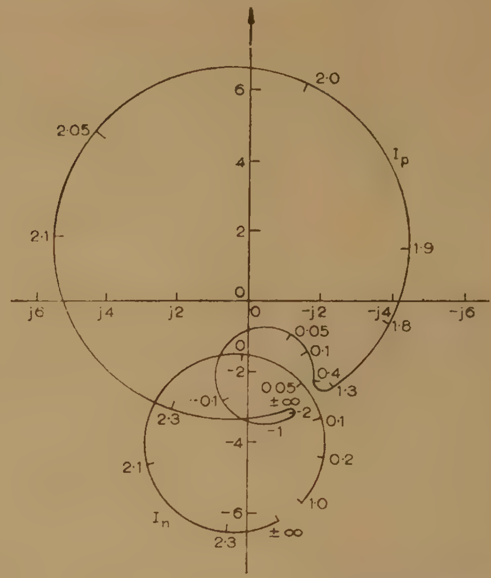


Fig. 3.—Loci of sequence currents, capacitor braking.
Numbers indicate slip. $Z_c = -j80$ ohms.

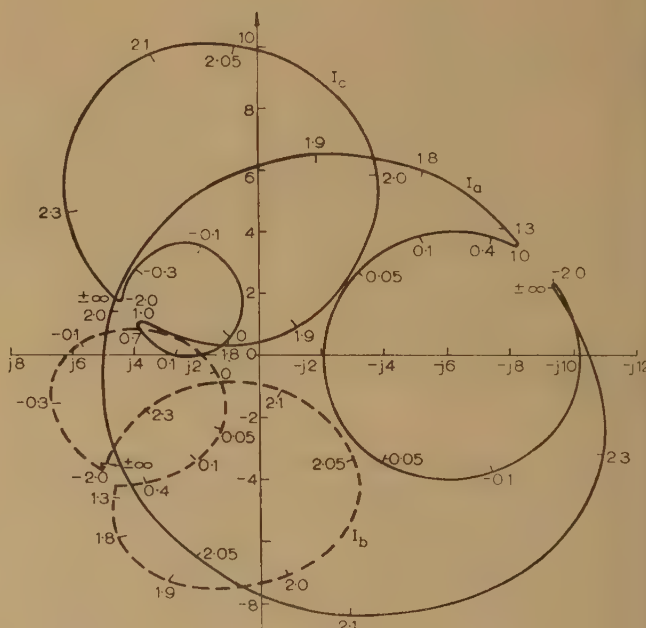


Fig. 4.—Loci of phase currents, capacitor braking.
Numbers indicate slip. $Z_c = -j80$ ohms.

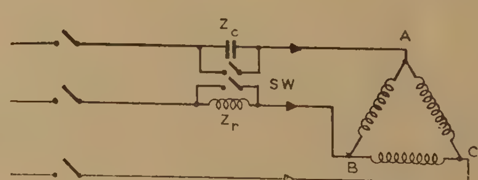


Fig. 5.—Capacitor-reactor braking.
SW open during braking period.

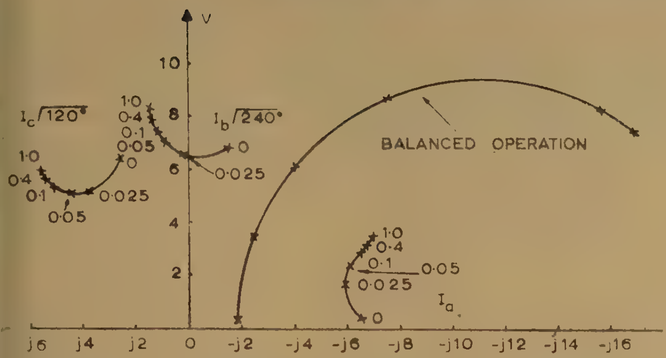


Fig. 6.—Loci of phase currents, capacitor-reactor braking.
Numbers indicate slip. $Z_c = -j80$ ohms, $Z_r = j40$ ohms.

The equations explain the advantages of capacitor-reactor braking over capacitor braking: I_p and I_n are reduced, but I_n/I_p is increased. Hence, with small capacitance a higher braking torque per ampere is obtained.

(2.4) Braking by Generator Action

If the main switch is opened, especially during the initial stages when the speed is high, and connections are made as shown in Fig. 7, the machine may work as a capacitor-excited

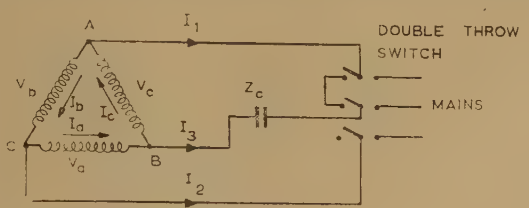


Fig. 7.—Braking by generator action.

induction generator, wasting the kinetic energy of the revolving masses as heat in the stator and rotor windings. The generator action can only continue if the speed is above a certain value which depends upon the value of the capacitor used.

$$I_a = I_p + I_n = I_b = I_p\angle 240° + I_n\angle 120°$$

Hence, $I_p = I_n\angle 120°$

$$I_c = I_p\angle 120° + I_n\angle 240°$$

$$I_1 = I_c - I_b = I_p\angle 120° + I_n\angle 240° - I_p\angle 240° - I_n\angle 120° = \sqrt{3}\angle 90°(I_p - I_n) = 3I_p\angle 120°$$

Hence, $I_p = \frac{I_1}{3}\angle 120°$, $I_n = \frac{I_1}{3}\angle 240°$

$$V_p = Z_pI_p = Z_p\frac{I_1}{3}\angle 120°$$

$$V_n = Z_nI_n = Z_n\frac{I_1}{3}\angle 240°$$

$$V_c = V_p\angle 120° + V_n\angle 240° = \frac{I_1}{3}(Z_p + Z_n)$$

Thus, V_c is determined by the point of intersection of the curve $\frac{I_1}{3}(Z_p + Z_n)$ with the straight line I_1Z_c.

Fig. 8 shows the experimental values of voltage and current

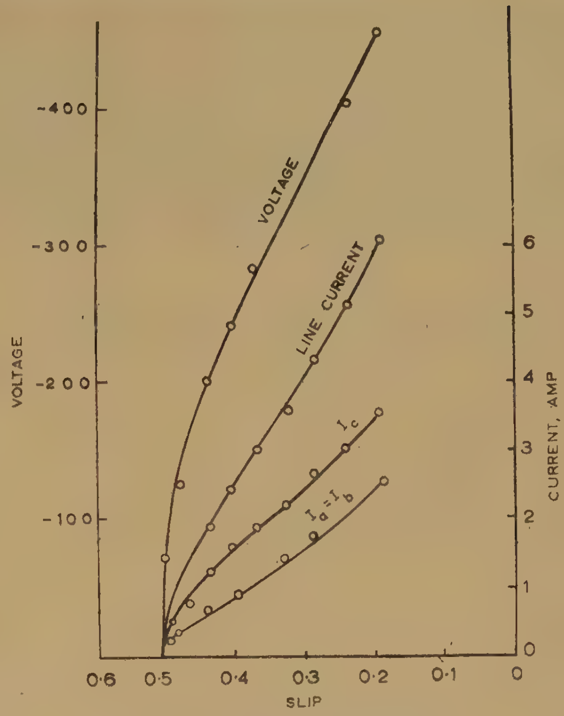


Fig. 8.—Braking by generator action.
One line open. $Z_c = -j60$ ohms.

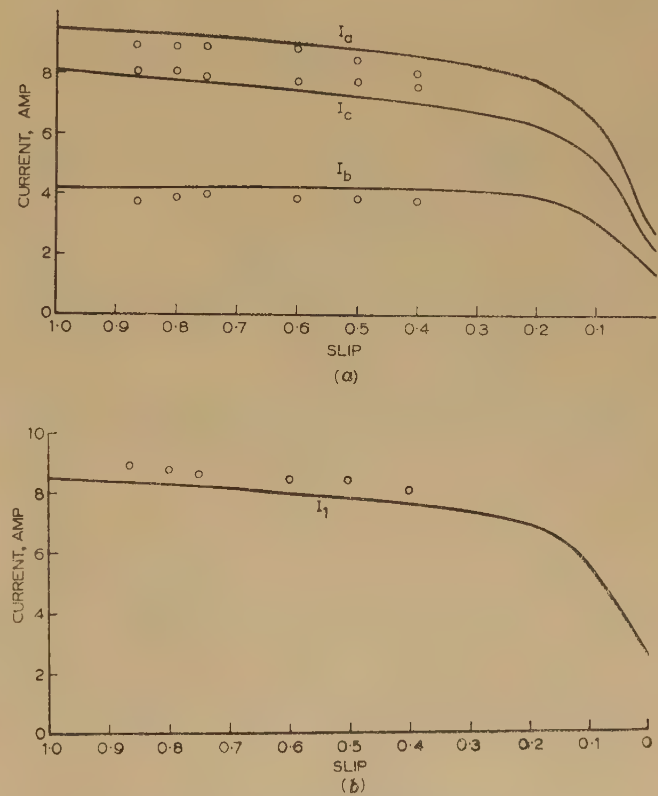


Fig. 9.—Capacitor braking.
(a) Phase currents. $Z_c = -j60$ ohms. ⊙ Test points.
(b) Capacitor current. $Z_c = -j60$ ohms. ⊙ Test points.

obtained for the test machine, when braking by generator action was used.

(3) CURRENT AND TORQUE VARIATIONS DURING THE BRAKING PERIOD

Figs. 9(*a*) and (*b*) show the winding currents and the current through the capacitor, respectively, when only a capacitor is used for braking. Figs. 10(*a*) and (*b*) show the corresponding

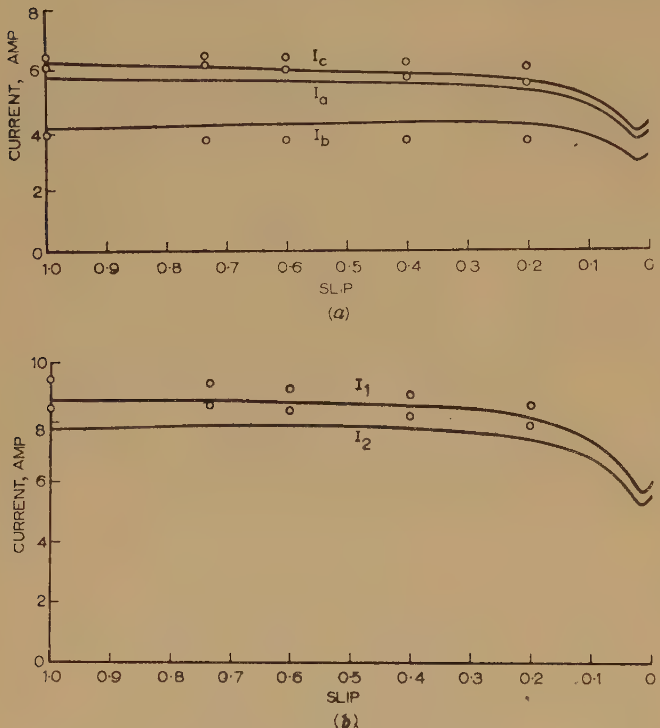


Fig. 10.—Capacitor-reactor braking.
(*a*) Phase currents. $Z_c = -j60$ ohms, $Z_r = j20$ ohms. ⊙ Test points.
(*b*) Capacitor and reactor currents. $Z_c = -j60$ ohms, $Z_r = j20$ ohms. ⊙ Test points.

quantities when capacitor-reactor braking is adopted. There is fairly good agreement between the test results and calculated values. The currents remain fairly steady from about 80% full speed down to standstill. The winding currents, I_a and I_c, in capacitor braking are much larger than the corresponding currents in capacitor-reactor braking.

Fig. 11 shows the calculated speed/torque characteristics for various values of capacitor. The positive or driving torque developed by the machine during the initial stages of braking

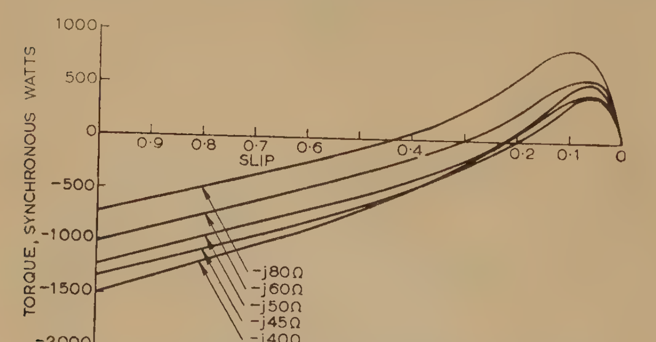


Fig. 11.—Torque/slip curves for various values of Z_c, capacitor braking.

may be noticed. So, unless the load torque is greater than the maximum torque developed by the motor, which may vary from 25% to 50% of the full-load torque, depending upon the capacitor used, the machine will not decelerate.

Fig. 12 shows the calculated speed/torque characteristics during capacitor-reactor braking. The introduction of a reactor

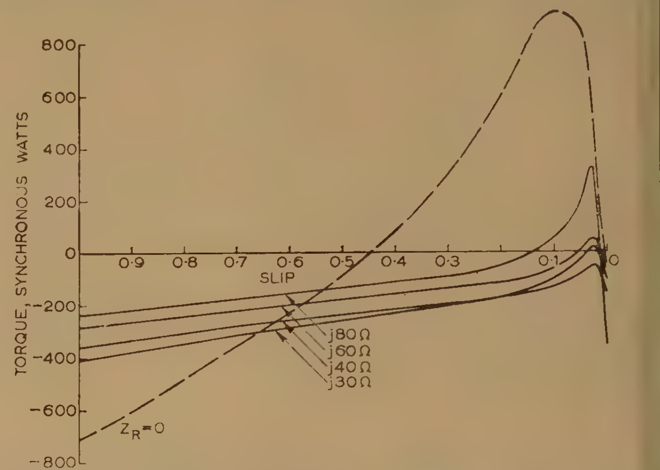


Fig. 12.—Torque/slip curves for various inductive reactances and a fixed capacitive reactance $Z_c = -j80$ ohms.

in another line reduces the driving torque in the initial stages, even though it reduces the braking torque at low speeds. With suitable values of capacitor and reactor, the machine can be made to develop only braking torque throughout the decelerating period. The reduction in the driving torque during the initial stages continues as the inductive reactance is reduced, down to a certain value; with further reduction the driving torque increases.

Fig. 13 shows the speed/torque characteristics for three operations:

(i) Braking by generator action with $Z_c = -j60$ ohms.
(ii) Capacitor braking with $Z_c = -j60$ ohms.
(iii) Capacitor-reactor braking with $Z_c = -j60$ ohms and $Z_r = j20$ ohms.

The first curve is experimental; curves (ii) and (iii) have been obtained by calculation, and some test points are shown for the sake of comparison.

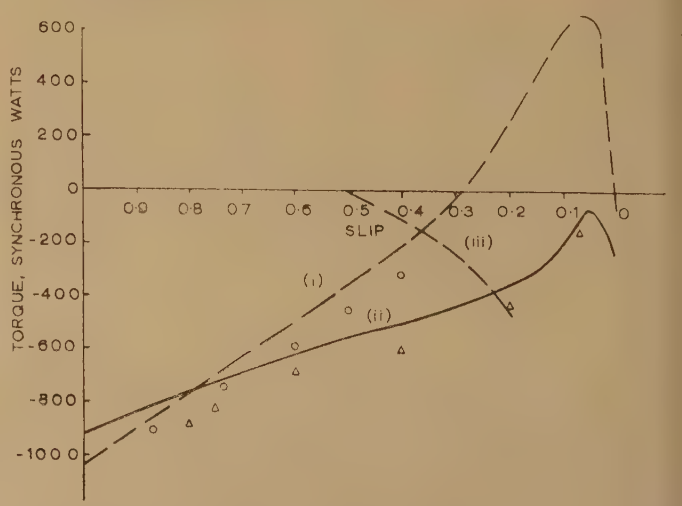


Fig. 13.—Torque/slip curves.
(i) Capacitor braking, $Z_c = -j60$ ohms. ⊙ Test points.
(ii) Capacitor-reactor braking, $Z_c = -j60$ ohms, $Z_r = j20$ ohms. △ Test points.
(iii) Braking by generator action.

(4) POWER INPUT, LOSSES, AND KINETIC ENERGY ABSORBED

Fig. 14 shows the power input to the machine (calculated as well as experimental) and losses in the machine (calculated) for the three cases of capacitor braking, capacitor-reactor braking and plugging. The difference between the ordinates of the two curves gives the power absorbed from the revolving masses. There is a considerable reduction in the power drawn from the lines during capacitor and capacitor-reactor braking.

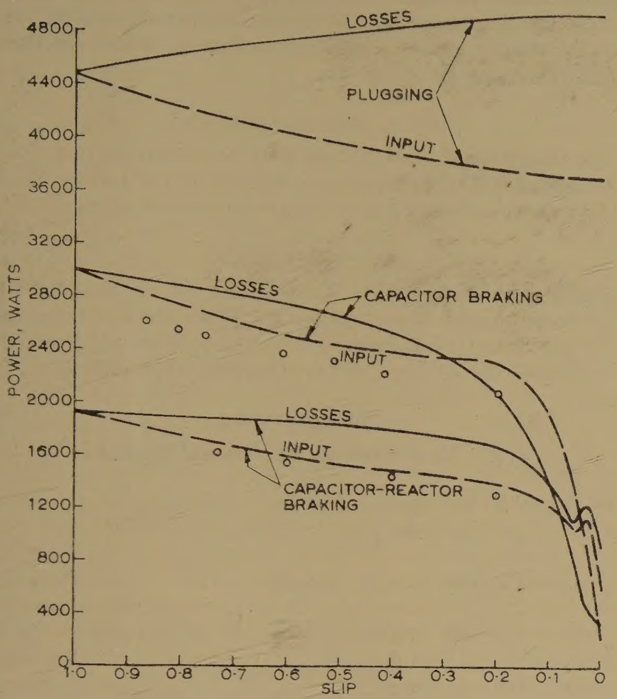


Fig. 14.—Input and losses.
⊙ Test points, input.

(5) BRAKING TIME AND TEMPERATURE RISE

Knowing the load torque and the motor torque during the braking period, the resultant braking-torque curve can be drawn. Over a convenient number of speed ranges this curve may be assumed to be linear, and by calculating the average braking torque over a particular speed range, the time required for the reduction of speed can be calculated. The sum of all these time intervals gives the total braking time. Adopting this procedure, the braking times for the four methods under consideration have been calculated, and are given in Table 1.

Proceeding along similar lines, the curves of Fig. 15 have been drawn showing how the losses vary during the braking period for the three cases. A constant-load torque of 1 000 synchronous

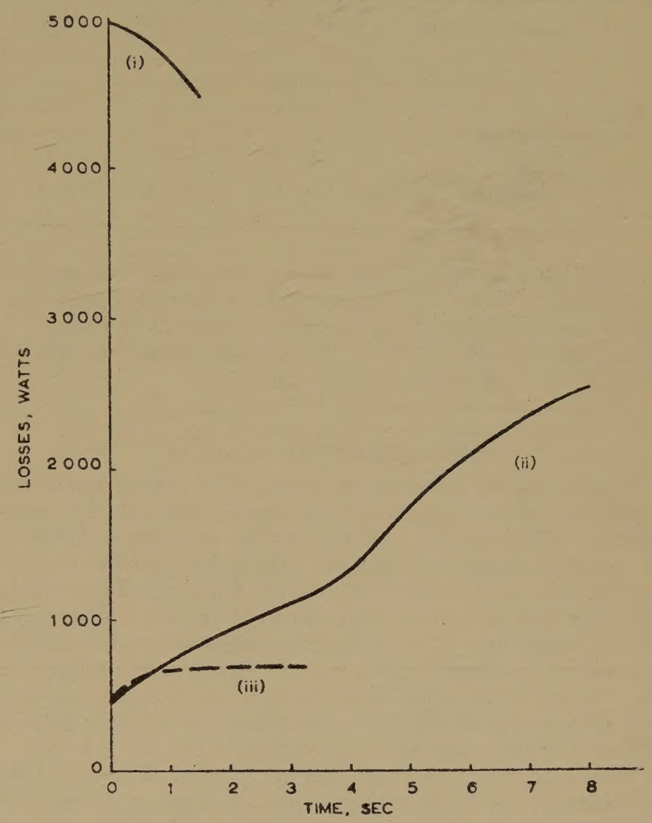


Fig. 15.—Loss/time curves.
Load torque constant, 1 000 synchronous watts.
(i) Plugging.
(ii) Capacitor braking.
(iii) Capacitor-reactor braking.

Table 1
Braking Times

Load torque	Method of braking	Braking time: Calculated	Braking time: Test
		sec	sec
Friction and windage losses only	Main switch open	—	39
	Plugging	2·04	—
	Capacitor braking ($-j80$ ohms)	∞	∞
	Mains cut off during the driving torque range, then capacitor braking ($-j80$ ohms)	19·87	17·8
	Induction generator during the driving torque range, then capacitor braking ($-j80$ ohms)	10·27	10
	Capacitor-reactor braking ($-j80$ ohms and $j40$ ohms)	11·3	10·5
1 000 synchronous watts (constant)	Main switch open	—	19
	Plugging	1·42	—
	Capacitor braking	8·05	7·6
	Capacitor-reactor braking	3·16	3·0

watts has been assumed. In the absence of a knowledge of the duty cycle of the machine, and of the thermal characteristics of its various components, no attempt was made to calculate the temperature rise with these methods of braking. Table 2,

Table 2

Calculated Energy Losses

(Constant-load torque, 1 000 synchronous watts)

Method of braking	Total energy loss	Average energy loss	Braking time
	kW-sec	kW-sec	sec
Plugging	6·56	4·63	1·42
Capacitor braking ($-j80$ ohms)	11·996	1·49	8·05
Capacitor-reactor braking ($-j80$ ohms and $+j40$ ohms)	2·108	0·668	3·16

showing the total energy loss, the average energy loss and the braking time, gives a comparative idea of the temperature rises which may be expected with the three methods of braking.

As Figs. 13 and 14 indicate, better results could be expected when $Z_c = -j60$ ohms and $Z_r = j20$ ohms.

(6) EXPERIMENTAL RESULTS

Considering the assumptions and approximations made, the agreement between calculated and experimental values is satisfactory. The induction motor under test was direct-coupled to a separately excited d.c. machine. The product of the armature current and field current of the d.c. machine, after making allowance for the torque required to overcome windage and friction losses and the iron loss, was taken as proportional to the torque developed by the motor. Except while testing for the braking time, when rated voltage was applied, reduced voltage was applied and the test results increased either proportionately or as the square of the voltage, as the case may be.

Air-core reactors were used and the moment of inertia of the rotating parts, as determined by a retardation test, was 3·84 lb-ft^2 corresponding to a stored energy constant of 0·8 kW-sec per kilovolt-ampere.

With the capacitor selected for braking, the machine did not build up voltage as a generator if all the three lines were connected together, but only when two lines were connected as in Fig. 7.

For satisfactory operation, it is seen from experiments that the capacitor kVA has to be equal to about 110% of the kVA input to the motor at full load, and the voltage across the capacitor is about 120% of the motor terminal voltage. The reactor kVA and voltage are about one-third of these values, which will depend on the constants of the motor.

(7) CONCLUSIONS

For many applications, where plugging is unsatisfactory owing to high rate of deceleration, heavy duty on the switching contacts, disturbances to the power system and the possibility of the load being driven in the reverse direction, capacitor or capacitor-reactor braking may be considered as an alternative. Capacitor-reactor braking is definitely more advantageous than capacitor braking, owing to the absence of the driving torque, and to the smaller energy and current drawn from the supply. Only for applications where the load itself exerts a considerable braking torque at high speeds, but a very low torque at low speeds, should capacitor braking be considered, as it avoids the use of a reactor and is a little more effective at low speeds than capacitor-reactor braking.

(8) ACKNOWLEDGMENT

The experiments and calculations were carried out by Mr. Viswanatha Rai, a post-graduate student of the Indian Institute of Technology, to whom the author expresses his thanks.

(9) REFERENCE

(1) Sreenivasan, T. V.: 'Application of a Variable-Reactor/Capacitor Combination for Reversing and Controlling the Speed of Polyphase Induction Motors', *Proceedings I.E.E.*, Paper No. 2697 U, October, 1958 (**105** A, p. 522).

(10) APPENDIX

(10.1) Derivation of the General Equation

Referring to Fig. 1:

$$V_a = V_1 - I_2 Z_r + I_3 Z_x$$

$$V_b = V_1 \angle\underline{240^\circ} - I_1 Z_c + I_2 Z_r$$

$$V_c = V_1 \angle\underline{120^\circ} + I_1 Z_c - I_3 Z_x$$

$$V_p = \tfrac{1}{3}(V_a + V_b \angle\underline{120^\circ} + V_c \angle\underline{240^\circ})$$

$$= V_1 + \frac{I_1 Z_c \diagup\overline{90^\circ} - I_2 Z_r \diagup\overline{30^\circ} + I_3 Z_x \angle\underline{30^\circ}}{\sqrt{3}}$$

$$V_n = \tfrac{1}{3}(V_a + V_b \angle\underline{240^\circ} + V_c \angle\underline{120^\circ})$$

$$= \frac{I_1 Z_c \angle\underline{90^\circ} - I_2 Z_r \angle\underline{30^\circ} + I_3 Z_x \diagup\overline{30^\circ}}{\sqrt{3}}$$

$$I_p = \frac{V_p}{Z_p} = \frac{V_1}{Z_p} + \frac{I_1 Z_c \diagup\overline{90^\circ} - I_2 Z_r \diagup\overline{30^\circ} + I_3 Z_x \angle\underline{30^\circ}}{(\sqrt{3}) Z_p}$$

$$I_n = \frac{V_n}{Z_n} = \frac{I_1 Z_c \angle\underline{90^\circ} - I_2 Z_r \angle\underline{30^\circ} + I_3 Z_x \diagup\overline{30^\circ}}{(\sqrt{3}) Z_n}$$

$$I_a = I_p + I_n,\ I_b = I_p \angle\underline{240^\circ} + I_n \angle\underline{120^\circ}$$

$$I_c = I_p \angle\underline{120^\circ} + I_n \angle\underline{240^\circ}$$

$$I_1 = I_b - I_c = (\sqrt{3})(I_p \diagup\overline{90^\circ} + I_n \angle\underline{90^\circ})$$

$$I_2 = I_a - I_b = (\sqrt{3})(I_p \angle\underline{30^\circ} + I_n \diagup\overline{30^\circ})$$

$$I_3 = I_c - I_a = (\sqrt{3})(I_p \angle\underline{150^\circ} - I_n \angle\underline{30^\circ})$$

By substituting these expressions for $I_1 - I_3$ in the expressions for I_p and I_n, eqns. (1)–(5) are obtained.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, JUNE 1959

CONTENTS

Bibliographical References.—It is requested that bibliographical reference to an Institution paper should always include the serial number of the paper and the month and year of publication, which will be found at the top right-hand corner of the first page of the paper. This information should precede the reference to the Volume and Part.

Example.—SMITH, J.: 'Overhead Transmission Systems', *Proceedings I.E.E.*, Paper No. 4001 S, December, 1954 (102 A, p. 1234).

Published by The Institution, Savoy Place, London, W.C.2. *Telephone:* COVent Garden 1871. *Telegrams:* 'Voltampere, Phone, London.
Printed by Unwin Brothers Limited, Woking and London.